BPRG User's Guide

BPRGs for Radionuclides

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PDF of User's Guide.

Welcome to the EPA's "Preliminary Remediation Goals for Radionuclides in Buildings at Superfund Sites" (BPRG) user's guide. Here you will find descriptions, equations and default exposure parameters used to calculate the risk-based PRGs. Additional guidance is also provided on sources of parameters and proper BPRG use. It is suggested that users read the BPRG FAQ page before proceeding. The user guide is extensive, so please use the "Open All Sections" and "Close All Sections" links below as needed. Individual sections can be opened and closed by clicking on the section titles. Before proceeding through the user's guide, please read the Disclaimer.

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Disclaimer

This guidance document sets forth recommended approaches based upon the current available and relevant science with respect to risk assessment for response actions at CERCLA sites. This document does not establish binding rules. Alternative approaches for risk assessment may be found to be more appropriate at specific sites (e.g., where site circumstances do not match the underlying assumptions, conditions, and models of the recommended guidance). The use of this recommended guidance or of alternate approaches in the consideration or selection of remedial or removal actions on CERCLA sites should be reflected in the Administrative Records for such sites. Accordingly, if comments are received at individual sites questioning the use of the approaches recommended in this guidance, the comments should be considered and an explanation provided for the selected approach.

The policies set out in the Radionuclide BPRG User's Guide provide guidance to EPA staff. It also provides recommended guidance to the public and regulated community on how EPA intends the National Oil and Hazardous Substances Pollution Contingency Plan (NCP) be implemented. EPA may change this recommended guidance in the future, as appropriate. This calculator is intended for use by risk assessors, health physicists, and other qualified environmental protection specialists.

It should also be noted that calculating a BPRG addresses neither human radionuclide dose or noncancer toxicity nor potential ecological risk. Of the radionuclides generally found at CERCLA sites, only uranium has potentially significant noncancer toxicity. When assessing sites with uranium as a contaminant, it may also be necessary to consider the noncancer toxicity of uranium using other tools, such as EPA's Regional Screening Levels (RSLs) for Chemical Contaminants at Superfund Sites electronic calculator for uranium in soil, water, or air and the WTC for uranium inside buildings. EPA's PRG Calculator should be used to assess radionuclide cancer risk in soil, water and air and the SPRG Calculator for cancer risk for hard outside surfaces. EPA's DCC Calculator should be used to assess radionuclide dose for soil, water, and air, BDCC Calculator for radionuclide dose inside buildings, and the SDCC Calculator for radionuclide dose for hard outside surfaces. Similarly, some sites with radiological contaminants in sensitive ecological settings may also need to be evaluated for potential ecological risk. EPA's guidance "Ecological Risk Assessment Guidance for Superfund: Process for Designing and Conducting Ecological Risk Assessment" contains an eight step process for using benchmarks for ecological effects in the remedy selection process.

1. Introduction

Generally, these recommended Preliminary Remediation Goals for Radionuclides in Buildings (BPRGs) are reasonable maximum exposure (RME) risk concentrations derived from standardized equations that combine exposure information and toxicity information in the form of slope factors (SFs). Recommended BPRGs are presented for resident and indoor worker exposure. The risk-based BPRGs for radionuclides are based on the carcinogenicity of the contaminants. Cancer slope factors (SFs) used are provided by the Center for Radiation Protection Knowledge. The main report is Calculations of Slope Factors and Dose Coefficients, and the tables of slope factors are in a separate appendix.

Generally under the NCP, PRGs are risk-based, protective screening values that can be used to identify areas and contaminants of potential concern (COPCs) that either do or do not warrant further investigation. PRGs typically are tools for evaluating and cleaning up contaminated sites. They are not *de facto* cleanup standards and should not be applied as such; however, they may be helpful in providing long-term targets to use during the analysis of remedial alternatives. In general, generic PRGs are used before site-specific risk assessments as a screening tool. After the baseline risk assessment, PRGs are typically refined to incorporate site-specific knowledge and conditions.

This recommended BPRG guidance is a tool that the U.S. Environmental Protection Agency has developed to help standardize the evaluation and cleanup of radioactively contaminated buildings. This guidance provides a recommended methodology for radiation professionals to calculate risk-based, site-specific, concentrations for radionuclides that comply with a risk-based standard, such as the 1E-04 to 1E-06 NCP risk range.

This calculator is based on Risk Assessment Guidance for Superfund: Volume I, Human Health Evaluation Manual (Part B, Development of Risk-based Preliminary Remediation Goals) (RAGS Part B). RAGS Part B provides guidance on using EPA toxicity values and exposure information to calculate risk-based recommended BPRGs. Recommended for initial use at the scoping phase of a project using readily available information, risk-based recommended BPRGs generally are modified based on site-specific data gathered during the RI/FS study. This website combines current EPA SFs with "standard" exposure factors to estimate contaminant concentrations in settled dust on surfaces, ambient air, and direct external exposure that are protective of humans (including sensitive groups) over a lifetime. Exceeding a recommended BPRG usually suggests that further evaluation of the potential risks is warranted. The recommended BPRG concentrations presented on this website can be used to screen pollutants, trigger further investigation, and provide initial cleanup goals, if applicable.

In addition to this guidance, for relevant training see the internet-based course, "Decontamination and Decommissioning of Radiologically Contaminated Facilities."

This website combines current Center for Radiation Protection Knowledge SFs with standard exposure factors to estimate contaminant concentrations in environmental media (biota, air, soil, and water) that are protective of humans (including sensitive groups) over a lifetime. Sufficient knowledge about a given site may warrant the use of site-specific assumptions that may differ from the defaults. Exceeding a BPRG usually suggests that further evaluation of the potential risks is appropriate. The BPRG concentrations presented on this website can be used to screen pollutants in environmental media, trigger further investigation, and provide initial cleanup goals, if applicable. BPRGs should be applied in accordance with guidance from EPA Regions.

The BPRG calculator was previously peer reviewed, and the documentation of that peer review may be seen here.

2. Understanding the BPRG Website

2.1 General Considerations

BPRGs are isotope concentrations that correspond to certain levels of risk from dust inside a building. Slope Factors (SFs) for a given radionuclide represent the risk equivalent per unit intake (i.e., ingestion or inhalation) or external exposure of that radionuclide. In risk assessments, these SFs are used in calculations with radionuclide concentrations and exposure assumptions to estimate risk from exposure to radioactive contamination. The calculations may be rearranged to generate BPRGs for a specified level of risk. SFs may be specified for specific body organs or tissues of interest or as a weighted sum of individual organ risk, termed the effective risk equivalent. These SFs may be multiplied by the total activity of each radionuclide inhaled or ingested per year, or the external exposure concentration to which a receptor may be exposed, to estimate the risk to the receptor. Slope Factors used are provided by the Center for Radiation Protection Knowledge. The main report is Calculations of Slope Factors and Dose Coefficients and the tables of DCFs are in a separate appendix.

Inhalation slope factors are tabulated separately for each of the three lung absorption types considered in the lung model currently recommended by the International Commission on Radiological Protection (ICRP) and, where appropriate, for inhalation of radionuclides in vapor or gaseous forms.

The designations "F", "M", and "S" presented in the Radionuclide Table under the heading "ICRP Lung Type" refer to the lung absorption type for inhaled particulate radionuclides, expressed as fast (F), medium (M), or slow (S), as used in the current ICRP model of the respiratory tract. The inhalation slope factor value tabulated in the Radionuclide Table for each radionuclide has been selected based on the following guidelines: (1) For those elements where Table 4.1 of Federal Guidance Report No. 13 (and Table 2 of ICRP Publication 72) specifies a recommended default lung absorption type for particulates, the inhalation slope factor for that type is tabulated in the Radionuclide Table for each radioisotope of that element. (2) For those elements where no specific lung absorption type is recommended and multiple types are indicated as plausible choices, the inhalation slope factor reported in the Radionuclide Table for each radioisotope of that element is the maximum of the values for each of the plausible lung absorption types. (3) If Federal Guidance Report No. 13 specifies risk coefficients for multiple chemical forms of certain elements (tritium, carbon, sulfur, iodine, and mercury), the inhalation slope factor value for the form estimated to pose the maximum risk is reported in the Radionuclide Table, in most cases.

Inhaled particulates are assumed to have an activity median aerodynamic diameter (AMAD) of 1 um, as recommended by the ICRP for consideration of environmental exposures in the absence of specific physical characteristics of the aerosol. Where appropriate, radionuclides may be present in gas or vapor form, are designated by "G" and "V", respectively; such radionuclides include tritium, carbon, sulfur, nickel, ruthenium, iodine, tellurium, and mercury.

The most likely exposure scenarios and exposure assumptions are included in the equations on this website: Resident, Indoor Worker.

The recommended BPRGs are generated with standard exposure route equations using EPA SFs and exposure parameters. For the calculation of soil ingestion slope factors, a standard soil density of 1.6 g/cm^3 has been used.

2.2 BPRG Output Options

The calculator offers three options for calculating BPRGs. Previous versions of this calculator employed slope factors that included progeny ingrowth for 100 years, designated "+D." The +D slope factors are no longer included in the pick list. This section describes the potential applications of the three choices and recommends a default BPRG calculation.

2.2.1 BPRG Output Option #1: Assumes Secular Equilibrium Throughout the Chain (no decay)

This is the preferred BPRG calculation option and is marked as the default selection in the calculator. When a single isotope is selected, the calculator identifies all the daughters in the chain. The BPRGs for each daughter are combined with the parent on a fractional basis. The fractional basis is determined by branching fractions where a progeny may decay into more than one isotope. The resulting BPRG is now based on secular equilibrium of the full chain. For straight chain decay, all the progeny would be at the same activity of the parent, and the BPRG provided in the output would be the inverse sum of the reciprocal BPRGs of the parent and all the progeny. Currently, all the soil BPRG equation images are presented with a radioactive decay term to account for half-lives shorter than the exposure duration. Decay is not included in this BPRG option, as the assumption of secular equilibrium is that the parent is continually being renewed.

When the secular equilibrium BPRG output option is selected, the BPRG Calculator now gives the option to show the individual progeny contributions for the BPRG (and risk) output. When the option to display progeny contribution is selected, the BPRG Calculator output gives the secular equilibrium BPRG and the individual progeny BPRGs in separate tables.

- A total BPRG is calculated using the following formula.

Total secular equilibrium BPRG for parent isotope;

$$BPRG_{SE\text{-}tot} = \frac{1}{\left(\sum_{i=1}^{n} \frac{1}{BPRG_{SE\text{-}route_i}}\right)}$$

where:
n = total number of exposure routes;

Route secular equilibrium BPRG for parent isotope:

$$BPRG_{SE\text{-}route} = \frac{1}{\left(\sum_{i=1}^{n} \frac{1}{\left(\frac{BPRG}{FC}\right)_i}\right)}$$

where:
n = total number of isotopes in decay chain;
FC = fractional contribution of isotope in decay chain;
BPRG = BPRG for isotope in decay chain without decay.

2.2.2 BPRG Output Option #2: Does Not Assume Secular Equilibrium, Provides Results for Progeny Throughout Chain (with decay)

This option displays the BPRGs calculated with half-life decay as identified in the BPRG equation images. In addition to the selected isotope, all the individual progeny BPRGs are displayed. Each BPRG is determined with each isotope's respective half-life and not that of its parent isotope. This option does not assume secular equilibrium and presents all the individual progeny BPRGs, so that the risk assessor can identify isotopes that will be present and measure their activities. Users can alter progeny half-life to match the parent isotope or other progeny or to account for ingrowth and decay over a chain.

2.2.3 BPRG Output Option #3: Does Not Assume Secular Equilibrium, No Progeny Included (with decay)

This option displays BPRGs for only the selected isotopes, with half-life decay as identified in the BPRG equation images. In this output, secular equilibrium is not assumed, progeny BPRGs are not displayed, and progeny contribution is not combined into the BPRG for the selected isotope. This option is useful when contamination is from one radionuclide with a very long half-life, where secular equilibrium would be too conservative.

2.3 Slope Factors (SFs)

EPA classifies all radionuclides as Group A carcinogens ("carcinogenic to humans"). Group A classification is used only when there is sufficient evidence from epidemiologic studies to support a causal association between exposure to the agents and cancer. The appendix radionuclide table, from the Center for Radiation Protection Knowledge, lists ingestion, inhalation and external exposure cancer slope factors (risk coefficients for total cancer morbidity) for radionuclides in conventional units of picocuries (pCi). Ingestion and inhalation slope factors are central estimates in a linear model of the age-averaged, lifetime attributable radiation cancer incidence (fatal and nonfatal cancer) risk per unit of activity inhaled or ingested, expressed as risk/pCi. External exposure slope factors are central estimates of lifetime attributable radiation cancer incidence risk for each year of exposure to external radiation from photon-emitting radionuclides distributed uniformly in a thick layer of soil, expressed as risk/yr per pCi/gram soil. External exposure slope factors can also be used that have units of risk/yr per pCi/cm^2 soil. When combined with site-specific media concentration data and appropriate exposure assumptions, slope factors can be used to estimate lifetime cancer risks to members of the general population due to radionuclide exposures. EPA currently provides guidance on inhalation risk assessment for chemicals in RAGS Part F (Risk Assessment Guidance for Superfund Volume I: Human Health Evaluation Manual, Part F, Supplemental Guidance for Inhalation Risk Assessment). The development of inhalation slope factors for radionuclides differs from the guidance presented in RAGS Part F.

The SFs from the Center for Radiation Protection Knowledge differ from the values presented in HEAST. The SFs were calculated using ORNL's DCAL software in the manner of Federal Guidance Report 12 and 13. For the calculation of soil ingestion slope factors, a standard soil density of 1.6 g/cm^3 has been used. The radionuclides presented are those provided in the International Commission on Radiological Protection (ICRP) Publication 107. This document contains a revised database of nuclear decay data (energies and intensities of emitted radiations, physical half-lives and decay modes) for 1,252 naturally occurring and manmade radionuclides. ICRP Publication 107 supersedes the previous database, ICRP Publication 38, published in 1983.

2.3.3 Metastable Isotopes

Most dose and risk coefficients are presented for radionuclides in their ground state. In the decay process, the newly formed nucleus may be in an excited state and emit radiation (e.g., gamma rays) to lose the energy of the state. The excited nucleus is said to be in a metastable state, which is denoted by the chemical symbol and atomic number appended by "m" (e.g., Ba-137m). If additional higher energy metastable states are present, then "n", "p", etc.... is appended. Metastable states have different physical half-lives and emit different radiations and thus unique dose and risk coefficients. In decay data tabulations of ICRP 107, if the half-life of a metastable state was less than 1 minute, then the radiations emitted in de-excitation are included with those of the parent radionuclide. Click to see a graphical representation of the decay of Cs-137 to Ba-137.

Eu-152, in addition to its ground state, has two metastable states: Eu-152m and Eu-152n. The half-lives of Eu-152, Eu-152m and Eu-152n are: 13.5 y, 9.31 m and 96 m, respectively, and the energy emitted per decay is 1.30 MeV, 0.080 MeV, and 0.14 MeV, respectively.

2.4 BPRG in Context of Superfund Modeling Framework

This recommended BPRG calculator focuses on the application of generic and simple site-specific approaches that are part of a larger framework for calculating concentration levels that are designed to be consistent with risk-based criteria. Generic recommended BPRGs for a 1 × 10^{-6} cancer risk standard are provided by viewing either the tables in the Download Area section of this calculator or by running the BPRG Search section of this calculator with the "Get Default BPRGs" option.

Generic recommended BPRGs can be calculated from the same equations presented in the site-specific portion of the calculator, but typically they are based on a number of default assumptions chosen to be protective of human health for most site conditions. Generic recommended BPRGs can be used in place of site-specific BPRG levels; however, in general, they are expected to be more protective than site-specific levels. The site manager should weigh the cost of collecting the data necessary to develop site-specific BPRGs with the potential for deriving a higher BPRG that provides an appropriate level of protection.

To avoid unnecessary inconsistency between radiological and chemical risk assessment and radiological dose assessment at the same site, users should generally use the same model for chemical and radionuclide risk assessment and radionuclide dose assessment. If there is a site-specific reason for using another model, justification for doing so should be developed. The justification should include specific supporting data and information in the administrative record. The justification normally would include the model runs, using both the recommended EPA BPRG model and the alternative model. Users are cautioned that they should have a thorough understanding of both the BPRG recommended model and any alternative model when evaluating whether a different approach is appropriate. When alternative models are used, the user should adjust the default input parameters to be as close as possible to the BPRG inputs, which may be difficult since models tend to use different definitions for parameters. Numerous computerized mathematical models have been developed by EPA and other organizations to predict the fate and transport of radionuclides in the environment; these models include single-media unsaturated zone models (e.g., groundwater transport) as well as multi-media models. These models have been designed for a variety of goals, objectives, and applications; as such, no single model may be appropriate for all site-specific conditions. Generally, even when a different model is used to predict fate and transport of radionuclides through different media, EPA recommends using the BPRG calculators for the remedial program to establish the risk-based concentrations to ensure consistency with CERCLA, the NCP and EPA's Superfund guidance for remedial sites. Prior to using another model for risk assessment at a CERCLA remedial site, EPA regional staff should consult with the Superfund remedial program's National Radiation Expert (Stuart Walker, (703) 603-8748 or walker.stuart@epa.gov. For more information on this issue, please see questions 10 and 16 on pages 12 and 17-18 of Radiation Risk Assessment At CERCLA Sites: Q & A (EPA 540-R-012-13, May 2014).

2.5 Understanding Risk Output on the BPRG Website

The BPRG calculator provides an option to select risk output. In the calculator, select "yes" if risk output is desired. Selecting risk output requires the calculator to be run in "Site Specific" mode. The risk values presented on this site are radionuclide-specific values for individual contaminants in air, dust, and 3-D external exposure that may warrant further investigation or site cleanup.

2.5.1 General Considerations for the Risk Output

This portion of the risk assessment process is generally referred to as "Risk Characterization". This step incorporates the outcome of the exposure and toxicity assessments to calculate the risk resulting from potential exposure to radionuclides via the pathways and routes of exposure determined appropriate for the source area.

The process used to calculate risk in this calculator does not follow the traditional method of first calculating a

CDI (Chronic Daily Intake). Rather, risk is derived using a simple method that relies on the linear nature of the relationship between concentration and risk. Using the equation below, a PRG, the target risk used to calculate the PRG, and a concentration entered by the user are all that is required to calculate risk.

TR/PRG = Risk/C

The linear equation above is then rearranged to solve for risk:

Risk = (C × TR) / PRG

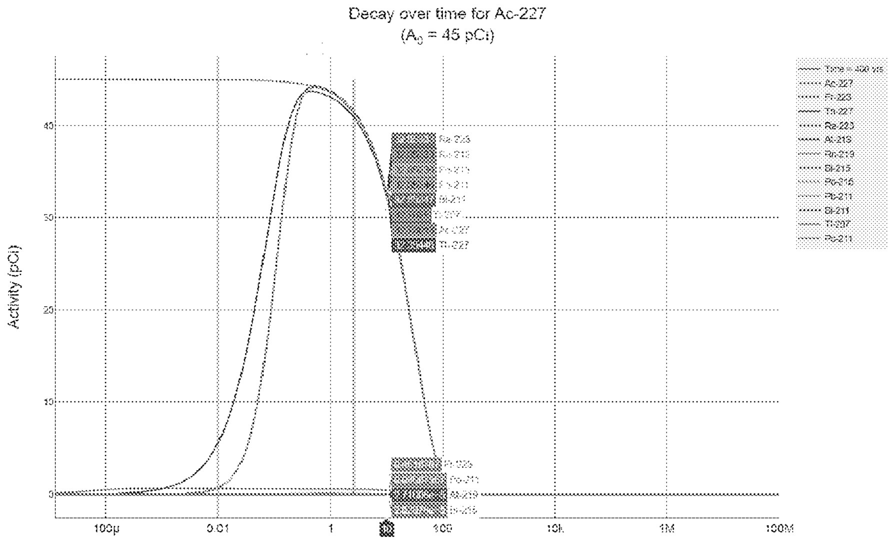
where:

Risk = a unitless probability of an individual developing cancer over a lifetime, determined with the equation above
C = Concentration entered by the user in site-specific mode [pCi/g ; pCi/cm^2 ; pCi/m^3]
TR = Target Risk provided by the user in site-specific mode
PRG = Preliminary Remediation Goal, determined by the values entered by the user in site-specific mode [pCi/g ; pCi/cm^2 ; pCi/m^3]

2.5.2 General Considerations for Entering Site Data

As presented in the previous section, the risk output is dependent on the BPRG calculated. Section 2.2 discusses the BPRG output options. To summarize section 2.2, the BPRG options are either secular equilibrium or not. If the data is collected from a site where secular equilibrium is assumed to be present, the user need only enter the activity of the parent in the calculator and a representative risk of the parent and all progeny will be presented in the calculator output. In the case of non-secular equilibrium, the current "state of the chain" may not be known or easily calculated. In the case of relatively fast decaying isotopes, significant decay or ingrowth of progeny may have occurred since the sample date. Further, determining future activity of the contaminants may be useful in planning for future release of a property.

A Decay Chain Activity Projection Tool has been developed where the user can select an isotope, enter a length of time to allow decay and ingrowth, and enter the beginning activity of the parent. The results of this tool, pictured below, are the activities of the parent and progeny at the end of the decay and ingrowth of progeny time. These activities can be entered into the BPRG calculator to calculate risk using the second and third BPRG Output options.



2.5.3 One-Hit Rule

The linear risk equation, listed above, is valid only at low risk levels (below estimated risks of 0.01). For sites where radiological exposure might be high (estimated risks above 0.01), the one-hit equation, which is consistent with the linear low-dose model, should be used instead (RAGS, part A, ch. 8). The results presented on the BPRG use this rule. In the following instances, the one-hit rule is used independently in the risk output tables:

- Risk from a single exposure route for a single radionuclide.
- Summation of single radionuclide risk (without one-hit rule applied to single radionuclide results) for multiple exposure routes (right of each row).
- Summation of risk (without one-hit rule applied to single radionuclide results) from a single exposure route for multiple radionuclides (bottom of each column).
- Summation of total risk (without one-hit rule applied to single radionuclide results or summations listed above) from multiple radionuclides across multiple exposure routes (bottom right hand cell).

3. Using the BPRG Table

The tables in the "BPRG Download Area" provide generic concentrations in the absence of site-specific exposure assessments. These screening concentrations can be used to:

- Prioritize multiple sites within a facility
- Set risk-based detection limits for contaminants of potential concern (COPCs)
- Focuse further assessment or response actions for the site or building

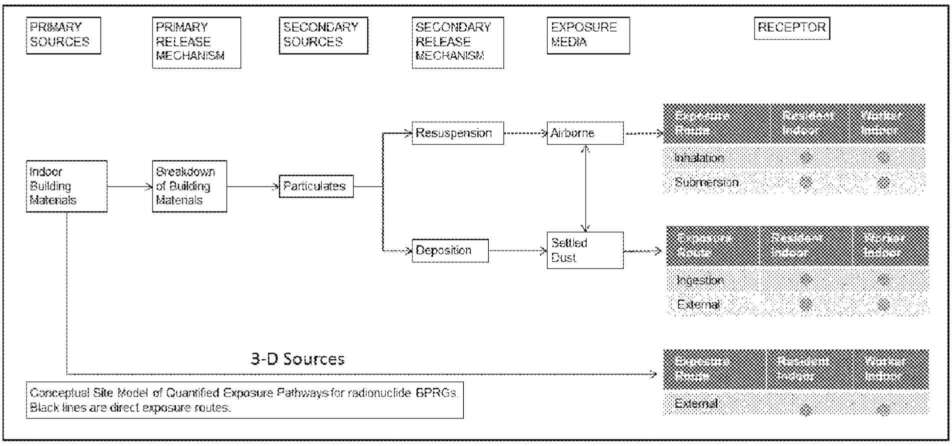
3.1 Developing a Conceptual Site Model

When using BPRGs, the exposure pathways of concern and site conditions should match those of the screening levels. Thus, normally, a conceptual site model (CSM) should be developed to identify likely contaminant source areas, exposure pathways, and potential receptors. This information can be used to determine the applicability of screening levels at the site and the need for additional information. The final CSM should represent linkages among contaminant sources, release mechanisms, exposure pathways, and routes and receptors based on historical information. Exposure routes could include: ingestion, inhalation, external exposure, or submersion. See Section 4.3.9 for the consideration of dermal exposure. A CSM should summarize the understanding of the contamination problem.

Existing EPA documents with additional CSM guidance are:

1. Risk Assessment Guidance for Superfund: Volume I Human Health Evaluation Manual (Part D, Standardized Planning, Reporting, and Review of Superfund Risk Assessments). See Planning Table 1; and
2. Soil Screening Guidance for Radionuclides: User's Guide. See Attachment A.

CSMs may be tabular, graphical, or stem-and-leaf. Section 4 of the user guide presents links to graphical CSMs for each scenario. Below is a stem-and-leaf CSM showing the exposure routes quantified and not quantified in this calculator.



As a final check, the CSM should answer the following questions:

- Are there potential ecological concerns?
- Is there potential for other uses of the building other than those covered by the recommended BPRG levels (e.g., agricultural, recreational, or trespasser)?
- Are there other likely human exposure pathways that were not considered in development of the recommended BPRG levels?
- Are there unusual site conditions?

The recommended BPRGs may need to be adjusted to reflect the answers to these questions, and additional tools or assessment methodologies may need to be considered (e.g., if there may be potentially significant ecological risk). The recommended default scenarios in this calculator are based the same default scenarios EPA provides in its guidance. Other scenarios may be investigated, using the BPRG calculator, by altering recommended site-specific exposure parameters.

3.2 Background Radiation

Natural background radiation should be considered before applying the recommended BPRGs to develop cleanup levels. Background and site-related levels of radiation should be addressed as they are for other hazardous substances, pollutants, and contaminants at CERCLA sites. For further information, see EPA's guidance "Role of Background in the CERCLA Cleanup Program", April 2002, (OSWER 9285.6-07P). It should be noted that certain ARARs may specifically address how to factor background into cleanup levels. For example, some radiation ARAR levels are established as increments above background concentrations. In these circumstances, background should be addressed in the manner prescribed by the ARAR. Additional information on radioactive materials present in building materials can be found in Volume 105, Number 2, March–April 2000, Journal of Research of the National Institute of Standards and Technology, Radioactivity Measurements on Glazed Ceramic Surfaces.

3.3 Potential Problems and Limitations

As with any risk/dose-based tool, the potential exists for misapplication. In most cases, this results from not understanding the intended use of the recommended BPRGs. In order to prevent misuse of the recommended BPRGs, follow these guidelines:

- Do not Apply recommended BPRG levels to a site without adequately developing a conceptual site model that identifies relevant exposure pathways and exposure scenarios.
- Do not use recommended BPRGs as cleanup levels without the consideration of other relevant criteria.
- Do not use recommended BPRGs as cleanup levels without verifying numbers with a health physicist/risk assessor.
- Do not use outdated recommended BPRG tables that have been superseded by more recent publications.
- Make sure to consider the effects from the presence of multiple isotopes.

4. Land Use Descriptions, Equations, and Technical Documentation

The recommended BPRGs consider human exposure from direct contact with contaminated dust and air and external exposure to contaminated building materials. The equations and technical discussion are aimed at developing concentration levels for risk-based cleanup. Calculation of the recommended BPRGs are based on the BPRG Calculator. The following text presents the recommended land use equations and their exposure routes. Table 1 presents the recommended definitions of the variables and their default values. Any alternative values or assumptions used in remedy evaluation or selection on a CERCLA site should be presented with supporting rationale in the Administrative Record.

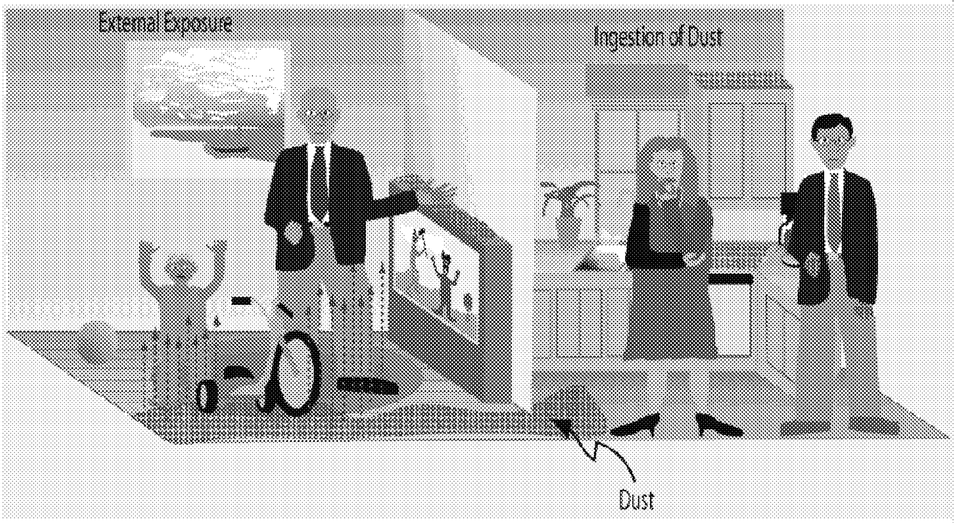
4.1 Resident

The recommended BPRG equations for the residential exposure scenario, presented here, contain the following exposure pathways and exposure routes:

4.1.1 Exposure to Settled Dust on Surfaces

The resident is exposed to radioactive contaminants in dust that settles in a building. Exposure is via two exposure routes: external exposure and ingestion. Ingestion of dust occurs when hands contact dust-laden surface and then come in contact with the mouth. Variation is allowed for contact with hard and soft surfaces, as the transfer to skin varies on surface type.

Graphical Representation



Equations

Ingestion:

$$BPRG_{res\text{-}dust\text{-}ing}\left(pCi/cm^2\right) = \frac{TR \times t_{res}\,(year) \times \lambda\left(\frac{1}{year}\right)}{\left(\frac{1-e^{-kt_{res}}}{kt_{res}}\right) \times \left(1-e^{-\lambda t_{res}}\right) \times SF_o\left(\frac{risk}{pCi}\right) \times IFD_{res\text{-}adj}\left(3{,}200{,}400\ cm^2\right) \times F_{in} \times F_i}$$

where:

$$IFD_{res\text{-}adj}\left(3{,}200{,}400\ cm^2\right) = \left(\begin{array}{l} \left\{\begin{array}{l} \left[\left(FTSS_h\,(0.5) \times EF_{res\text{-}c}\left(\frac{350\ days}{year}\right) \times ET_{res\text{-}c,h}\left(\frac{6\ hours}{day}\right)\right) + \left(FTSS_s\,(0.1) \times EF_{res\text{-}c}\left(\frac{350\ days}{year}\right) \times ET_{res\text{-}c,s}\left(\frac{10\ hours}{day}\right)\right)\right] \times \\ SE\,(0.5) \times ED_{res\text{-}c}\,(6\ years) \times SA_{res\text{-}c}\left(\frac{16\ cm^2}{event}\right) \times FQ_c\left(\frac{17\ events}{hour}\right) \end{array}\right\} + \\ \left\{\begin{array}{l} \left[\left(FTSS_h\,(0.5) \times EF_{res\text{-}a}\left(\frac{350\ days}{year}\right) \times ET_{res\text{-}a,h}\left(\frac{6\ hours}{day}\right)\right) + \left(FTSS_s\,(0.1) \times EF_{res\text{-}a}\left(\frac{350\ days}{year}\right) \times ET_{res\text{-}a,s}\left(\frac{10\ hours}{day}\right)\right)\right] \times \\ SE\,(0.5) \times ED_{res\text{-}a}\,(20\ years) \times SA_{res\text{-}a}\left(\frac{49\ cm^2}{event}\right) \times FQ_a\left(\frac{3\ events}{hour}\right) \end{array}\right\} \end{array}\right)$$

External:

$$BPRG_{res\text{-}dust\text{-}ext}\left(pCi/cm^2\right) = \frac{TR \times t_{res}\,(year) \times \lambda\left(\frac{1}{year}\right)}{\left(\frac{1-e^{-kt_{res}}}{kt_{res}}\right) \times \left(1-e^{-\lambda t_{res}}\right) \times SF_{ext\text{-}gp}\left(\frac{risk/year}{pCi/cm^2}\right) \times F_{in} \times F_i \times F_{AM} \times F_{OFF\text{-}SET} \times ET_{res}\left(\frac{24\ hours}{day}\right) \times \left(\frac{1\ day}{24\ hours}\right) \times EF_{res}\left(\frac{350\ days}{year}\right) \times \left(\frac{1\ year}{365\ days}\right) \times ED_{res}\,(26\ years)}$$

Total:

$$BPRG_{res\text{-}dust\text{-}tot}\left(pCi/cm^2\right) = \frac{1}{\frac{1}{BRPG_{res\text{-}dust\text{-}ing}} + \frac{1}{BPRG_{res\text{-}dust\text{-}ext}}}$$

The resulting units for this recommended BPRG are in pCi/cm². The units are based on area, because the SF used is the ground plane for external exposure, and the ingestion route is based on hand surface area contacting dust on surfaces and subsequent hand to mouth transfer events. This equation is for values of k that are greater than 0; when k=0, the dissipation term is not quantified to avoid division by zero.

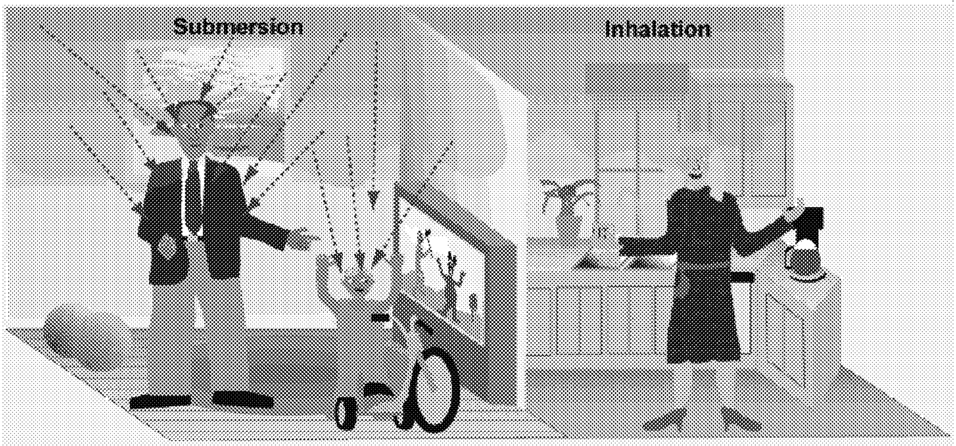
Definitions of the input variables are in Table 1.

4.1.2 Exposure to Ambient Air With Half-life Decay Exposure

Ambient air exposure equations are presented below. These equations include a half-life decay function. In situations where the contaminant in the air is not being replenished (e.g., contaminated settled dust from a previous release that is being resuspended), these equations should be used.

The resident is exposed to air in the home via two exposure routes. The first exposure route is inhalation of air. Inhalation is assumed to occur for the entire twenty-four hour day. The second exposure route is submersion. Submersion is external exposure from the contaminated air.

Graphical Representation



Equations

Inhalation:

$$BPRG_{res\text{-}air\text{-}decay\text{-}inh}\left(pCi/m^3\right) = \frac{TR \times t_{res}\,(year) \times \lambda\left(\frac{1}{year}\right)}{\left(1-e^{-\lambda t_{res}}\right) \times SF_i\left(\frac{risk}{pCi}\right) \times IFA_{res\text{-}adj}\left(161{,}000\ m^3\right) \times F_{in} \times F_i}$$

where:

$$IFA_{res\text{-}adj}\left(161{,}000\ m^3\right) = \left(\begin{array}{l}\left[ED_{res\text{-}c}\,(6\ years) \times IRA_{res\text{-}c}\left(\frac{10\ m^3}{day}\right) \times ET_{res\text{-}c}\left(\frac{24\ hours}{day}\right) \times \left(\frac{1\ day}{24\ hours}\right) \times EF_{res\text{-}c}\left(\frac{350\ days}{year}\right)\right] + \\ \left[ED_{res\text{-}a}\,(20\ years) \times IRA_{res\text{-}a}\left(\frac{20\ m^3}{day}\right) \times ET_{res\text{-}a}\left(\frac{24\ hours}{day}\right) \times \left(\frac{1\ day}{24\ hours}\right) \times EF_{res\text{-}a}\left(\frac{350\ days}{year}\right)\right]\end{array}\right)$$

Submersion:

$$BPRG_{res\text{-}air\text{-}decay\text{-}sub}\left(pCi/m^3\right) = \frac{TR \times t_{res}\,(year) \times \lambda\left(\frac{1}{year}\right)}{\left(1-e^{-\lambda t_{res}}\right) \times SF_{sub}\left(\frac{risk/year}{pCi/m^3}\right) \times GSF_a \times F_{in} \times F_i \times ET_{res}\left(\frac{24\ hours}{day}\right) \times \left(\frac{1\ day}{24\ hours}\right) \times EF_{res}\left(\frac{350\ days}{year}\right) \times \left(\frac{1\ year}{365\ days}\right) \times ED_{res}\,(26\ years)}$$

Total:

$$BPRG_{res\text{-}air\text{-}decay\text{-}tot}\left(pCi/m^3\right) = \frac{1}{\frac{1}{BRPG_{res\text{-}air\text{-}decay\text{-}inh}} + \frac{1}{BPRG_{res\text{-}air\text{-}decay\text{-}sub}}}$$

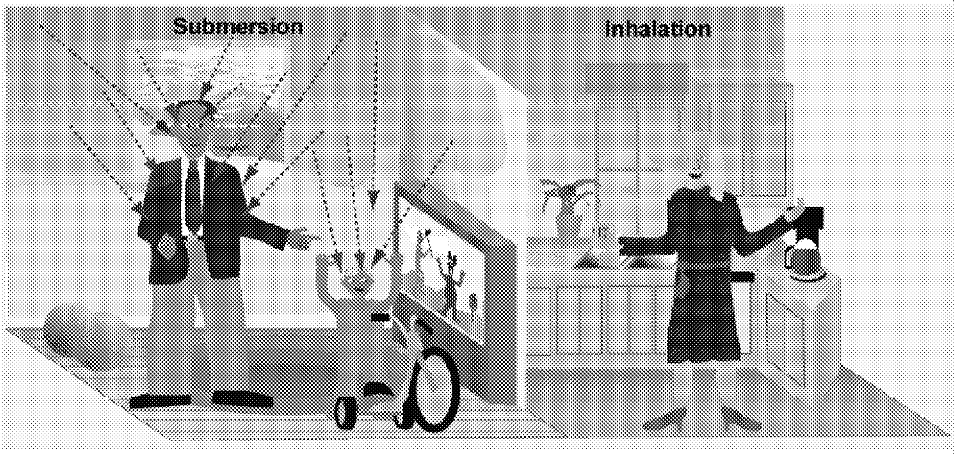
Definitions of the input variables are in Table 1.

4.1.3 Exposure to Ambient Air Without Half-life Decay Exposure

Ambient air exposure equations are presented below. These equations do not include a half-life decay function. In situations where the contaminant in the air has a continual source (e.g., indoor radon from radium in the soil), these equations should be used.

The resident is exposed to air in the home via two exposure routes. The first exposure route is inhalation of air. Inhalation is assumed to occur for the entire twenty-four hour day. The second exposure route is submersion. Submersion is external exposure from the contaminated air.

Graphical Representation



Equations

Inhalation:

$$BPRG_{res\text{-}air\text{-}nodecay\text{-}inh}\left(pCi/m^3\right) = \frac{TR}{SF_i\left(\frac{risk}{pCi}\right)\times IFA_{res\text{-}adj}\left(161{,}000\ m^3\right)\times F_{in}\times F_i}$$

where:

$$IFA_{res\text{-}adj}\left(161{,}000\ m^3\right) = \left[\begin{array}{l}\left[ED_{res\text{-}c}\left(6\ years\right)\times IRA_{res\text{-}c}\left(\frac{10\ m^3}{day}\right)\times ET_{res\text{-}c}\left(\frac{24\ hours}{day}\right)\times\left(\frac{1\ day}{24\ hours}\right)\times EF_{res\text{-}c}\left(\frac{350\ days}{year}\right)\right]+\\ \left[ED_{res\text{-}a}\left(20\ years\right)\times IRA_{res\text{-}a}\left(\frac{20\ m^3}{day}\right)\times ET_{res\text{-}a}\left(\frac{24\ hours}{day}\right)\times\left(\frac{1\ day}{24\ hours}\right)\times EF_{res\text{-}a}\left(\frac{350\ days}{year}\right)\right]\end{array}\right]$$

Submersion:

$$BPRG_{res\text{-}air\text{-}nodecay\text{-}sub}\left(pCi/m^3\right) = \frac{TR}{SF_{sub}\left(\frac{risk/year}{pCi/m^3}\right)\times GSF_a\times F_{in}\times F_i\times ET_{res}\left(\frac{24\ hours}{day}\right)\times\left(\frac{1\ day}{24\ hours}\right)\times EF_{res}\left(\frac{350\ days}{year}\right)\times\left(\frac{1\ year}{365\ days}\right)\times ED_{res}\left(26\ years\right)}$$

Total:

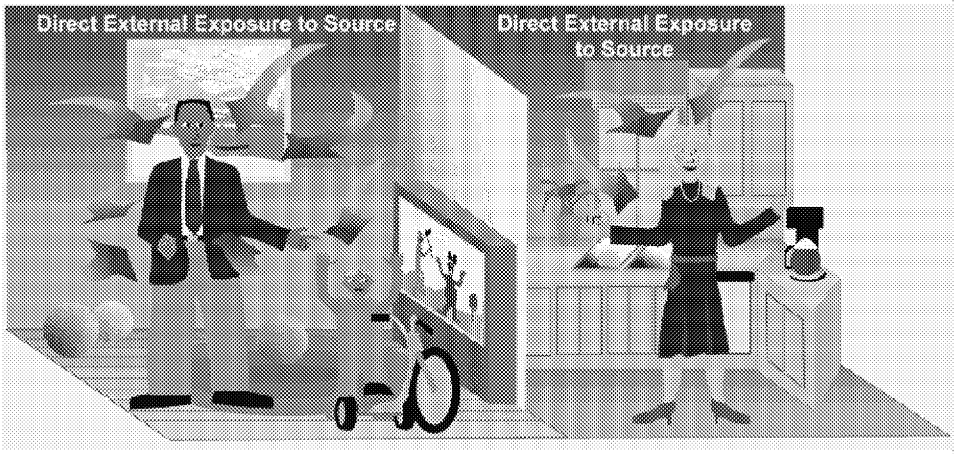
$$BPRG_{res\text{-}air\text{-}nodecay\text{-}tot}\left(pCi/m^3\right) = \frac{1}{\frac{1}{BRPG_{res\text{-}air\text{-}nodecay\text{-}inh}}+\frac{1}{BPRG_{res\text{-}air\text{-}nodecay\text{-}sub}}}$$

Definitions of the input variables are in Table 1.

4.1.4 3-D Direct External Exposure

The resident is exposed to radioactive contaminants in the building materials of the walls, floor and ceiling. Direct external exposure from these contaminants is the only exposure route in this scenario. This scenario uses various soil volume and ground plane slope factors.

Graphical Representation



Equations

Contaminated building materials in walls, floor and ceiling using soil volume toxicity values

ED_006060A_00002441-00009

$$BPRG_{res\text{-}3D\text{-}ext\text{-}sv}\,(pCi/g) = \frac{TR \times t_{res}\,(year) \times \lambda \left(\frac{1}{year}\right)}{\left(1-e^{-\lambda t_{res}}\right) \times SF_{ext\text{-}sv}\left(\frac{risk/year}{pCi/g}\right) \times GSF_b \times F_{in} \times F_i \times F_{AM} \times F_{OFF\text{-}SET} \times F_{r\text{-}surf^{sv}} \times ET_{res}\left(\frac{24\ hours}{day}\right) \times \left(\frac{1\ day}{24\ hours}\right) \times EF_{res}\left(\frac{350\ days}{year}\right) \times \left(\frac{1\ year}{365\ days}\right) \times ED_{res}\,(26\ years)}$$

Contaminated building materials in walls, floor and ceiling using 1cm soil volume toxicity values

$$BPRG_{res\text{-}3D\text{-}ext\text{-}1cm}\,(pCi/g) = \frac{TR \times t_{res}\,(year) \times \lambda}{\left(1-e^{-\lambda t_{res}}\right) \times SF_{ext\text{-}1cm}\left(\frac{risk/year}{pCi/g}\right) \times GSF_b \times F_{in} \times F_i \times F_{AM} \times F_{OFF\text{-}SET} \times F_{r\text{-}surf^{1cm}} \times ET_{res}\left(\frac{24\ hours}{day}\right) \times \left(\frac{1\ day}{24\ hours}\right) \times EF_{res}\left(\frac{350\ days}{years}\right) \times \left(\frac{1\ year}{365\ days}\right) \times ED_{res}\,(26\ years)}$$

Contaminated building materials in walls, floor and ceiling using 5cm soil volume toxicity values

$$BPRG_{res\text{-}3D\text{-}ext\text{-}5cm}\,(pCi/g) = \frac{TR \times t_{res}\,(year) \times \lambda \left(\frac{1}{year}\right)}{\left(1-e^{-\lambda t_{res}}\right) \times SF_{ext\text{-}5cm}\left(\frac{risk/year}{pCi/g}\right) \times GSF_b \times F_{in} \times F_i \times F_{AM} \times F_{OFF\text{-}SET} \times F_{r\text{-}surf^{5cm}} \times ET_{res}\left(\frac{24\ hours}{day}\right) \times \left(\frac{1\ day}{24\ hours}\right) \times EF_{res}\left(\frac{350\ days}{year}\right) \times \left(\frac{1\ year}{365\ days}\right) \times ED_{res}\,(26\ years)}$$

Contaminated building materials in walls, floor and ceiling using 15cm soil volume toxicity values

$$BPRG_{res\text{-}3D\text{-}ext\text{-}15cm}\,(pCi/g) = \frac{TR \times t_{res}\,(year) \times \lambda \left(\frac{1}{year}\right)}{\left(1-e^{-\lambda t_{res}}\right) \times SF_{ext\text{-}15cm}\left(\frac{risk/year}{pCi/g}\right) \times GSF_b \times F_{in} \times F_i \times F_{AM} \times F_{OFF\text{-}SET} \times F_{r\text{-}surf^{15cm}} \times ET_{res}\left(\frac{24\ hours}{day}\right) \times \left(\frac{1\ day}{24\ hours}\right) \times EF_{res}\left(\frac{350\ days}{year}\right) \times \left(\frac{1\ year}{365\ days}\right) \times ED_{res}\,(26\ years)}$$

Contaminated dust on walls, floor and ceiling using ground plane toxicity values

$$BPRG_{res\text{-}3D\text{-}ext\text{-}gp}\,\left(pCi/cm^2\right) = \frac{TR \times t_{res}\,(year) \times \lambda \left(\frac{1}{year}\right)}{\left(1-e^{-\lambda t_{res}}\right) \times SF_{ext\text{-}gp}\left(\frac{risk/year}{pCi/cm^2}\right) \times GSF_b \times F_{in} \times F_i \times F_{AM} \times F_{OFF\text{-}SET} \times F_{r\text{-}surf^{gp}} \times ET_{res}\left(\frac{24\ hours}{day}\right) \times \left(\frac{1\ day}{24\ hours}\right) \times EF_{res}\left(\frac{350\ days}{year}\right) \times \left(\frac{1\ year}{365\ days}\right) \times ED_{res}\,(26\ years)}$$

The resulting units for this recommended BPRG are in pCi/cm^2. The units are based on area, because the SF used is the ground plane for external exposure, and the ingestion route is based on hand surface area contacting dust on surfaces and subsequent hand to mouth transfer events.

Definitions of the input variables are in Table 1.

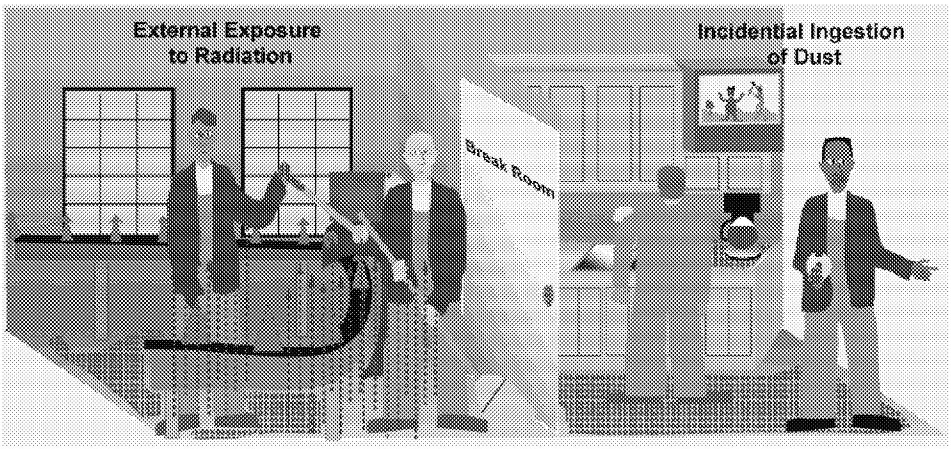
4.2 Indoor Worker

The recommended BPRG equations for the indoor worker exposure scenario, presented here, contain the following exposure pathways and exposure routes:

4.2.1 Exposure to Dust on Settled Surfaces

This worker is exposed to the radioactive contaminants in dust that settles in the building. Exposure is via two exposure routes: external exposure and ingestion. Ingestion of dust occurs when hands contact dust-laden surfaces and then come in contact with the mouth. Variation is allowed for contact with hard and soft surfaces, as the transfer to skin varies on surface type.

Graphical Representation



Equations

Ingestion:

$$BPRG_{iw\text{-}dust\text{-}ing}\left(pCi/cm^2\right) = \frac{TR \times t_{iw}\,(year) \times \lambda\left(\frac{1}{year}\right)}{\left(\frac{1-e^{-kt_{iw}}}{kt_{iw}}\right) \times \left(1-e^{-\lambda t_{iw}}\right) \times SF_{oa}\left(\frac{risk}{pCi}\right) \times IFD_{iw}\left(\frac{176.4\ cm^2}{day}\right) \times F_{in} \times F_i \times EF_{iw}\left(\frac{250\ days}{year}\right) \times ED_{iw}\,(25\ years)}$$

where:

$$IFD_{iw}\left(\frac{176.4\ cm^2}{day}\right) = \left[\left(FTSS_h\,(0.5) \times ET_{iw,h}\left(\frac{4\ hours}{day}\right)\right) + \left(FTSS_s\,(0.1) \times ET_{iw,s}\left(\frac{4\ hours}{day}\right)\right)\right] \times SE\,(0.5) \times SA_{iw}\left(\frac{49\ cm^2}{event}\right) \times FQ_{iw}\left(\frac{3\ event}{hour}\right)$$

External:

$$BPRG_{iw\text{-}dust\text{-}ext}\left(pCi/cm^2\right) = \frac{TR \times t_{iw}\,(year) \times \lambda\left(\frac{1}{year}\right)}{\left(\frac{1-e^{-kt_{iw}}}{kt_{iw}}\right) \times \left(1-e^{-\lambda t_{iw}}\right) \times SF_{ext\text{-}gp}\left(\frac{risk/year}{pCi/cm^2}\right) \times F_{in} \times F_i \times F_{AM} \times F_{OFF\text{-}SET} \times ET_{iw}\left(\frac{8\ hours}{day}\right) \times \left(\frac{1\ day}{24\ hours}\right) \times EF_{iw}\left(\frac{250\ days}{year}\right) \times \left(\frac{1\ year}{365\ days}\right) \times ED_{iw}\,(25\ years)}$$

Total:

$$BPRG_{iw\text{-}dust\text{-}tot}\left(pCi/cm^2\right) = \frac{1}{\frac{1}{BRPG_{iw\text{-}dust\text{-}ing}} + \frac{1}{BPRG_{iw\text{-}dust\text{-}ext}}}$$

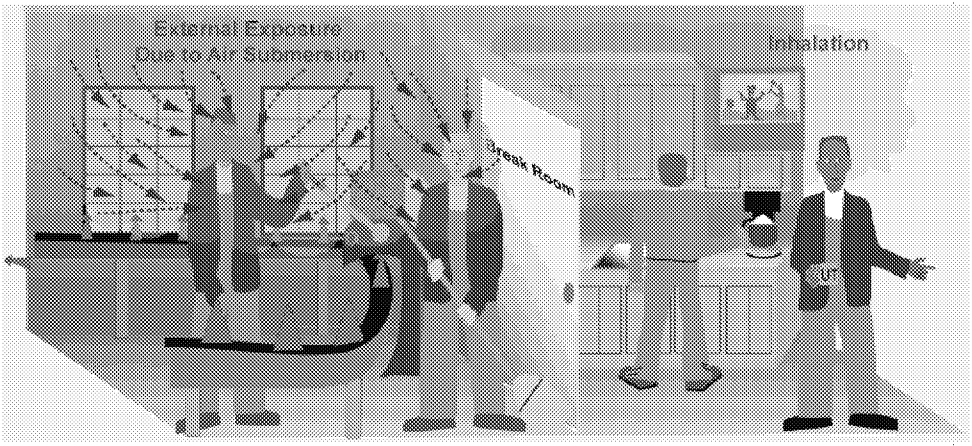
The resulting units for this recommended BPRG are in pCi/cm^2. The units are based on area, because the SF used is the ground plane for external exposure, and the ingestion route is based on hand surface area contacting dust on surfaces and subsequent hand to mouth transfer events. This equation is for values of k that are greater than 0; when k=0, the dissipation term is not quantified to avoid division by zero.

Definitions of the input variables are in Table 1.

4.2.2 Exposure to Ambient Air With half-life Decay

Ambient air exposure equations are presented below. These equations include a half-life decay function. In situations where the contaminant in the air is not being replenished (e.g., contaminated settled dust from a previous release that is being resuspended), these equations should be used. This worker is exposed to air in the building via two exposure routes. The first exposure route is inhalation of air. Inhalation is assumed to occur for the entire eight hour work day. The second exposure route is submersion. Submersion is external exposure from the contaminated air.

Graphical Representation



Equations

Inhalation:

$$BPRG_{iw\text{-}air\text{-}decay\text{-}inh}\left(pCi/m^3\right) = \frac{TR \times t_{iw}\,(year) \times \lambda\left(\frac{1}{year}\right)}{\left(1-e^{-\lambda t_{iw}}\right) \times SF_i\left(\frac{risk}{pCi}\right) \times IRA_{iw}\left(\frac{60\ m^3}{day}\right) \times F_{in} \times F_i \times ET_{iw}\left(\frac{8\ hours}{day}\right) \times \left(\frac{1\ day}{24\ hours}\right) \times EF_{iw}\left(\frac{250\ days}{year}\right) \times ED_{iw}\,(25\ years)}$$

Submersion:

$$BPRG_{iw\text{-}air\text{-}decay\text{-}sub}\left(pCi/m^3\right) = \frac{TR \times t_{iw}\,(year) \times \lambda\left(\frac{1}{year}\right)}{\left(1-e^{-\lambda t_{iw}}\right) \times SF_{sub}\left(\frac{risk/year}{pCi/m^3}\right) \times GSF_a \times F_{in} \times F_i \times ET_{iw}\left(\frac{8\ hours}{day}\right) \times \left(\frac{1\ day}{24\ hours}\right) \times EF_{iw}\left(\frac{250\ days}{year}\right) \times \left(\frac{1\ year}{365\ days}\right) \times ED_{iw}\,(25\ years)}$$

Total:

$$BPRG_{iw\text{-}air\text{-}decay\text{-}tot}\left(pCi/cm^2\right) = \frac{1}{\frac{1}{BRPG_{iw\text{-}air\text{-}decay\text{-}inh}} + \frac{1}{BPRG_{iw\text{-}air\text{-}decay\text{-}sub}}}$$

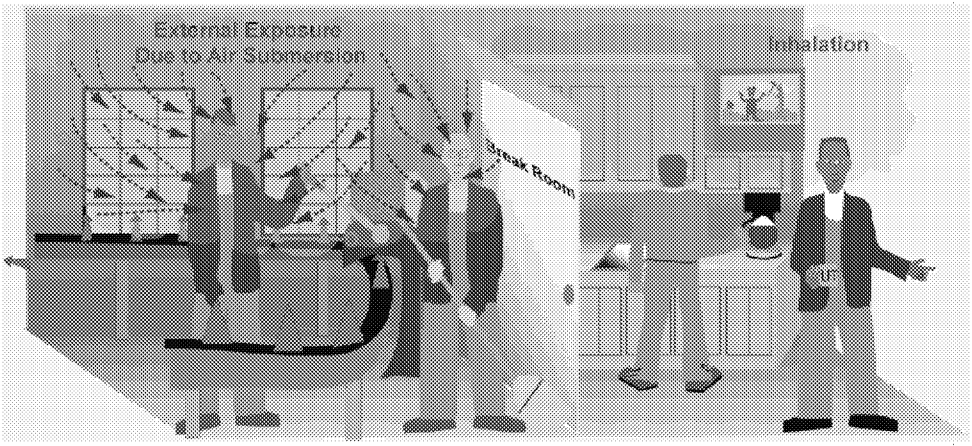
Definitions of the input variables are in Table 1.

4.2.3 Exposure to Ambient Air Without Half-life Decay

Ambient air exposure equations are presented below. These equations do not include a half-life decay function. In situations where the contaminant in the air has a continual source (e.g., indoor radon from radium in the soil), these equations should be used.

This worker is exposed to air in the building via two exposure routes. The first exposure route is inhalation of air. Inhalation is assumed to occur for the entire eight hour work day. The second exposure route is submersion. Submersion is external exposure from the contaminated air.

Graphical Representation



Equations

Inhalation:

$$BPRG_{iw\text{-}air\text{-}nodecay\text{-}inh}\left(pCi/m^3\right) = \frac{TR}{SF_i\left(\frac{risk}{pCi}\right)\times IRA_{iw}\left(\frac{60\ m^3}{day}\right)\times F_{in}\times F_i\times ET_{iw}\left(\frac{8\ hours}{day}\right)\times\left(\frac{1\ day}{24\ hours}\right)\times EF_{iw}\left(\frac{250\ days}{year}\right)\times ED_{iw}\left(25\ years\right)}$$

Submersion:

$$BPRG_{iw\text{-}air\text{-}nodecay\text{-}sub}\left(pCi/m^3\right) = \frac{TR}{SF_{sub}\left(\frac{risk/year}{pCi/m^3}\right)\times GSF_a\times F_{in}\times F_i\times ET_{iw}\left(\frac{8\ hours}{day}\right)\times\left(\frac{1\ day}{24\ hours}\right)\times EF_{iw}\left(\frac{250\ days}{year}\right)\times\left(\frac{1\ year}{365\ days}\right)\times ED_{iw}\left(25\ years\right)}$$

Total:

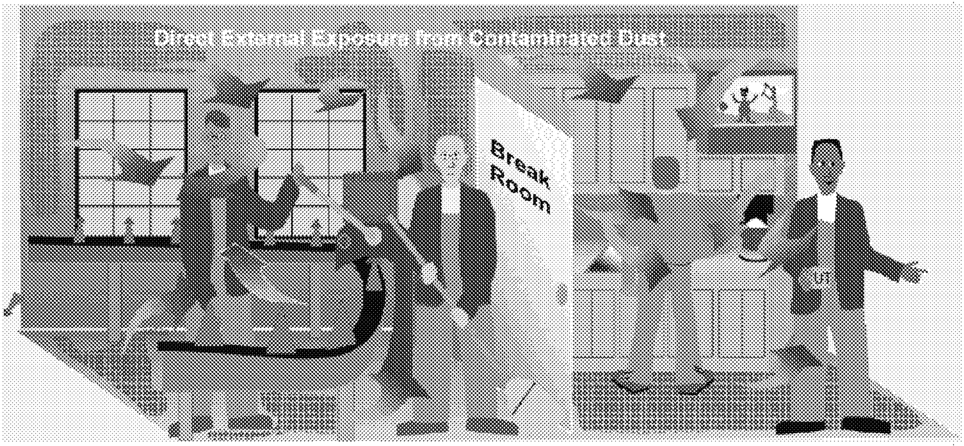
$$BPRG_{iw\text{-}air\text{-}nodecay\text{-}tot}\left(pCi/cm^3\right) = \frac{1}{\frac{1}{BRPG_{iw\text{-}air\text{-}nodecay\text{-}inh}}+\frac{1}{BPRG_{iw\text{-}air\text{-}nodecay\text{-}sub}}}$$

Definitions of the input variables are in Table 1.

4.2.4 3-D Direct External Exposure

This worker is exposed to radioactive contaminants in settled dust on the walls, floor and ceiling. Direct external exposure from the contaminants in the dust is the only exposure route in this scenario. This scenario uses various soil volume and ground plane slope factors.

Graphical Representation



Equations

Contaminated building materials in walls, floor and ceiling using soil volume toxicity values

$$BPRG_{iw\text{-}3D\text{-}ext\text{-}sv}\ (pCi/g) = \frac{TR \times t_{iw}\ (year) \times \lambda \left(\frac{1}{year}\right)}{\left(1\text{-}e^{-\lambda t_{iw}}\right) \times SF_{ext\text{-}sv} \left(\frac{risk/year}{pCi/g}\right) \times GSF_b \times F_{in} \times F_i \times F_{AM} \times F_{OFF\text{-}SET} \times F_{r\text{-}surf^{sv}} \times ET_{iw} \left(\frac{8\ hours}{day}\right) \times \left(\frac{1\ day}{24\ hours}\right) \times EF_{iw} \left(\frac{250\ days}{year}\right) \times \left(\frac{1\ year}{365\ days}\right) \times ED_{iw}\ (25\ years)}$$

Contaminated building materials in walls, floor and ceiling using 1cm soil volume toxicity values

$$BPRG_{iw\text{-}3D\text{-}ext\text{-}1cm}\ (pCi/g) = \frac{TR \times t_{iw}\ (year) \times \lambda \left(\frac{1}{year}\right)}{\left(1\text{-}e^{-\lambda t_{w}}\right) \times SF_{ext\text{-}1cm} \left(\frac{risk/year}{pCi/g}\right) \times GSF_b \times F_{in} \times F_i \times F_{AM} \times F_{OFF\text{-}SET} \times F_{r\text{-}surf^{1cm}} \times ET_{iw} \left(\frac{8\ hours}{day}\right) \times \left(\frac{1\ day}{24\ hours}\right) \times EF_{iw} \left(\frac{250\ days}{year}\right) \times \left(\frac{1\ year}{365\ days}\right) \times ED_{iw}\ (25\ years)}$$

Contaminated building materials in walls, floor and ceiling using 5cm soil volume toxicity values

$$BPRG_{iw\text{-}3D\text{-}ext\text{-}5cm}\ (pCi/g) = \frac{TR \times t_{iw}\ (year) \times \lambda \left(\frac{1}{year}\right)}{\left(1\text{-}e^{-\lambda t_{iw}}\right) \times SF_{ext\text{-}5cm} \left(\frac{risk/year}{pCi/g}\right) \times GSF_b \times F_{in} \times F_i \times F_{AM} \times F_{OFF\text{-}SET} \times F_{r\text{-}surf^{5cm}} \times ET_{iw} \left(\frac{8\ hours}{day}\right) \times \left(\frac{1\ day}{24\ hours}\right) \times EF_{iw} \left(\frac{250\ days}{year}\right) \times \left(\frac{1\ year}{365\ days}\right) \times ED_{iw}\ (25\ years)}$$

Contaminated building materials in walls, floor and ceiling using 15cm soil volume toxicity values

$$BPRG_{iw\text{-}3D\text{-}ext\text{-}15cm}\ (pCi/g) = \frac{TR \times t_{iw}\ (year) \times \lambda \left(\frac{1}{year}\right)}{\left(1\text{-}e^{-\lambda t_{w}}\right) \times SF_{ext\text{-}15cm} \left(\frac{risk/year}{pCi/g}\right) \times GSF_b \times F_{in} \times F_i \times F_{AM} \times F_{OFF\text{-}SET} \times F_{r\text{-}surf^{15cm}} \times ET_{iw} \left(\frac{8\ hours}{day}\right) \times \left(\frac{1\ day}{24\ hours}\right) \times EF_{iw} \left(\frac{250\ days}{year}\right) \times \left(\frac{1\ year}{365\ days}\right) \times ED_{iw}\ (25\ years)}$$

Contaminated dust on walls, floor and ceiling using ground plane toxicity values

$$BPRG_{iw\text{-}3D\text{-}ext\text{-}gp} \left(pCi/cm^2\right) = \frac{TR \times t_{w}\ (year) \times \lambda \left(\frac{1}{year}\right)}{\left(1\text{-}e^{-\lambda t_{w}}\right) \times SF_{ext\text{-}gp} \left(\frac{risk/year}{pCi/cm^2}\right) \times GSF_b \times F_{in} \times F_i \times F_{AM} \times F_{OFF\text{-}SET} \times F_{r\text{-}surf^{gp}} \times ET_{iw} \left(\frac{8\ hours}{day}\right) \times \left(\frac{1\ day}{24\ hours}\right) EF_{iw} \left(\frac{250\ days}{year}\right) \times \left(\frac{1\ year}{365\ days}\right) \times ED_{iw}\ (25\ years)}$$

The resulting units for this recommended BPRG are in pCi/cm^2. The units are based on area, because the SF used is the ground plane for external exposure, and the ingestion route is based on hand surface area contacting dust on surfaces and subsequent hand to mouth transfer events.

Definitions of the input variables are in Table 1.

4.3 Exposure Parameter Justification

The following sections describe the exposure parameter default variables and values. The default parameter values are listed in Table 1.

4.3.1 Exposure Time (ET)

The exposure time represents the hours per day that a receptor spends exposed to a source. The exposure times vary by exposure scenario, age of the receptor, and whether the source is located on a hard or soft surface. The EPA Office of Pesticide Programs (OPP) recommended defaults for a child resident are 8 hr/d for carpets and 4 hr/d for hard surfaces. Hard surface time is based on the estimated time spent in the kitchen and bathroom. Carpet time is based on remaining indoor time not including sleeping. This recommendation was judged to be representative of many children under age 6, who spend most of their time at home. After 18, many individuals will spend more time in school or at work. Others, however, may not work or attend school and spend more time at home. To be protective, it was decided to recommend this second scenario and assume that adult residents would spend 8 hr/d on soft surfaces (carpet, sofa, etc.) and 4 hr/d on hard surfaces. This totals 12 hr/d. Assuming that an individual sleeps 8 hr/d, the total time in a residence is 20 hr/d. For this calculator, the remaining 4 hr/d were equally divided between exposure to hard and soft surfaces. This results in recommended default values of 10 hr/d on carpets and 6 hr/d on hard surfaces for adult and child residents. Ingestion of settled dust while sleeping is considered negligible, because dust doesn't collect between sheets. Note that inhalation and subsequent ingestion of dust particles trapped in mucous is not quantified in the recommended BPRG equations due to lack of exposure information; however, exposure to ambient air and direct external exposure continues during sleep. Additional dust ingestion may occur during food preparation or storage on hard surfaces but is not quantified in the recommended BPRG equations due to lack of exposure information.

For the indoor worker, exposure time for the dust ingestion exposure route is also divided between exposure to hard and soft surfaces. For this calculator, the recommended defaults were set at 4 hr/d for hard and soft surfaces. The recommended exposure time for exposure to ambient air and direct external exposure is the entire work day, or 8 hr/d.

4.3.2 Fraction Transferred from Surface to Skin (FTSS)

In general, this is the fraction of residue on a surface that can be transferred to skin. US EPA 2003 (pg D-5) states that hand press experiments were conducted on dry skin. Transfers of 10% were observed for carpets and 50% were observed for hard surfaces. These recommendations are considered representative of the WTC situation and were adopted for this calculator.

4.3.3 Surface Area (SA)

In general, this is the skin area contacted during the mouthing event. The OPP recommended default was based on the surface area of the 3 fingers that a child will most likely use for hand to mouth transfer. It was assumed that 3 fingers of one hand represents about 5% of the total area of both hands (EPA 2003). The exposure factor handbook (EPA 2011, Table 7.2) presents hand surface areas for adults and children. For children, the surface areas were time-weight averaged across all age groups from birth to 6 years (317 cm^2), and the 5% assumption was applied to derive the child hand surface area of 16 cm^2.

The hand surface area for the adult was also derived from data presented in the exposure factor handbook (EPA 2011, Table 7.2). The exposure factor handbook presents hand surface areas for adult males and females of 1070 and 890 cm^2, respectively. These numbers were averaged to 980 cm^2, and the 5% assumption was applied to derive the adult hand surface area of 49 cm^2.

4.3.4 Frequency of Hand to Mouth (FQ)

The exposure factors handbook (EPA 2011, Table 4-1) and the World Trade Center report (EPA 2003) provide hand to mouth contact rates for many age groups. For the child FQ, all age groups for mean indoor contact from birth to 6 years old were time-weight averaged from the exposure factor handbook. Missing data points were substituted with data from the nearest age group. The FQ for children was determined to be 17 times/hr.

For the adult FQ, all age groups for mean indoor contact from 6 to 26 years old were time-weight averaged from the exposure factor handbook and World Trade Center report. The FQ for adults was determined to be 3 times/hr.

4.3.5 Saliva Extraction Factor (SE)

In general, the fraction transferred from skin to mouth will depend on the contaminant, mouthing time, and other behavioral patterns. The OPP recommended default is 50%, based on pesticide studies. Michaud et al (1994) assumed that all of the residues deposited on the fingertips would be transferred to the mouth, twice per day. In the Binghamton re-entry guideline derivation, a range of factors were used: 0.05, 0.1, and 0.25, representing the fraction of residue on hand that is transferred to the mouth (Kim and Hawley, 1985). For purposes of this assessment, the OPP recommended default of 50% was selected for all ages.

4.3.6 Age-Adjusted Dust Ingestion Rate (IF)

To account for the variability in exposure activities between children and adults, a recommended age-adjusted dust ingestion rate equation was developed. This equation is designed to take into account the differences in hand to mouth behavior, hand surface area, and exposure to hard and soft surfaces over the exposure durations of an adult and child.

4.3.7 Dust Ingestion Rate (IR_d)

To account for the variability in exposure to hard and soft surfaces, a recommended dust ingestion rate equation was developed. This equation averages the differences in exposure to hard and soft surfaces by the exposure times.

4.3.8 Dissipation Rate Constant (k)

In some circumstances, the load of dust on a contaminated surface to which receptors are exposed may decline over time. Dissipation of dust may result from cleaning and transfer to skin and clothing. Different surfaces may be cleaned at different rates, and any dissipation rate used should consider a representative cleaning frequency. To determine whether dissipation is a factor at a given site, the site manager should establish whether a significant reservoir of contaminated dust is present. Such reservoirs may function as sources of dust and negate the impacts of dissipation mechanisms. In fact, indoor concentrations of contaminants may be enhanced above their original outdoor source levels after repeated transfer inside (Paustenbach et al). The recommended first step in identifying the presence of a reservoir is to examine site history. If a waste site was created through disposal, deposition, or equipment leaks over an extended period of time, then the contaminant may have seeped deep into the surface. Porous surfaces such as cement or wood are also more likely to have subsurface contamination. When reservoirs are less likely to exist, such as at sites where contamination is the result of a single spill, dust cloud, or event, it may be more important to account for dissipation of surface loads. For fixed contamination in building materials or on material surfaces in the 3-D equations, the dissipation term is not included as dissipation is not expected.

The recommended default value for the dissipation rate constant, 0.0, assumes that a contaminant reservoir is present. This variable is adjustable in the recommended BPRG calculator. If a dissipation rate constant is used, it is generally assumed that the dust was deposited as a one-time event (i.e., dust cloud). Also, if a dissipation rate is applied, it is assumed that it is applicable from recommended BPRG calculation time onward. The discussion below provides a review of the literature related to this issue and provides an alternative dissipation rate constant value. Site specific dissipation rate constants can be used. This equation is for values of k that are greater than 0; when k=0, the dissipation term is not quantified to avoid division by zero. See the following text.

Based on many studies presented in EPA 2003 (pg. D-5), there is strong support for considering dissipation in setting criteria for building clean-ups. A study of the Binghamton State office Building found that dioxin has dissipated over time, according to first order kinetics, with a 20 to 22 month half-life. This dissipation is thought to occur from a combination of cleaning, resuspension, and dilution with uncontaminated dust (and possibly some volatilization). These same physical dissipation processes would apply to other compounds addressed in this study as well. Therefore, the other compounds were assumed to dissipate at the same rate as dioxin. In summary, a 22 month half-life (dissipation rate constant of 0.38 yr^{-1}) was adopted. Exposures were calculated in a series of time steps, where the residue level was assumed to dissipate according to first order kinetics: $CSL = CSL_{initial}\, e^{-kt}$, where

CSL = Contaminant Surface Load (μ/cm^2)
$CSL_{initial}$ = Initial Contaminant Surface Load ($\mu g/cm^2$)
k = Dissipation Rate Constant (1/yr)
t = Time (yr)

The above equation steps are shown for completeness. This recommended BPRG calculator computes a concentration of contaminants in dust that will not exceed a target risk. The equation simply derives the amount of dust. For this recommended BPRG calculator, the only parts of the equation that are relevant are the dissipation rate constant and time. By putting these variables in the denominator of the recommended BPRG resident and worker ingestion of dust equations, a higher recommended BPRG concentration would be calculated.

WARNING: Using a dissipation rate constant or changing the value of *t* should only be done once a complete understanding of the mathematics involved in deriving the equation is gained and after the site conditions have been fully investigated. The following exhibits display the results obtained by changing the value *t* and k. *t* is equal to ED in all equations.

In the simplified PRG equation: PRG=TR/CDI*SF*$(1-e^{(-kt)})/(kt)$, where PRG is preliminary remediation goal, TR is target risk, CDI is chronic daily intake, SF is the radionuclide-specific slope factor, and $(1-e^{(-kt)})/(kt)$ is the dissipation term. Exhibit 1 shows the results of changing *t*. Exhibit 2 shows the results of changing k.

Exhibit 1. Results Obtained By Changing The Value *t*.

t	k	SF	CDI	TR	$(1-e^{(-kt)})/(kt)$	PRG
yr	yr-1	risk/pCi	cm^2	risk	unitless	pCi/cm^2
0	0.38	1.00E-05	400	1.00E-06	1.00E+01	2.5E-04
1	0.38	1.00E-05	400	1.00E-06	8.32E-01	3.01E-04
2	0.38	1.00E-05	400	1.00E-06	7.00E-01	3.57E-04
3	0.38	1.00E-05	400	1.00E-06	5.97E-01	4.19E-04
4	0.38	1.00E-05	400	1.00E-06	5.14E-01	4.86E-04
5	0.38	1.00E-05	400	1.00E-06	4.48E-01	5.59E-04
6	0.38	1.00E-05	400	1.00E-06	3.94E-01	6.35E-04
7	0.38	1.00E-05	400	1.00E-06	3.50E-01	7.15E-04
8	0.38	1.00E-05	400	1.00E-06	3.13E-01	7.98E-04
9	0.38	1.00E-05	400	1.00E-06	2.83E-01	8.84E-04
10	0.38	1.00E-05	400	1.00E-06	2.57E-01	9.72E-04
11	0.38	1.00E-05	400	1.00E-06	2.36E-01	1.06E-03
12	0.38	1.00E-05	400	1.00E-06	2.17E-01	1.15E-03
13	0.38	1.00E-05	400	1.00E-06	2.01E-01	1.24E-03
14	0.38	1.00E-05	400	1.00E-06	1.87E-01	1.34E-03
15	0.38	1.00E-05	400	1.00E-06	1.75E-01	1.43E-03
16	0.38	1.00E-05	400	1.00E-06	1.64E-01	1.52E-03
17	0.38	1.00E-05	400	1.00E-06	1.55E-01	1.62E-03

18	0.38	1.00E-05	400	1.00E-06	1.46E-01	1.71E-03
19	0.38	1.00E-05	400	1.00E-06	1.38E-01	1.81E-03
20	0.38	1.00E-05	400	1.00E-06	1.32E-01	1.90E-03
21	0.38	1.00E-05	400	1.00E-06	1.25E-01	2.00E-03
22	0.38	1.00E-05	400	1.00E-06	1.20E-01	2.09E-03
23	0.38	1.00E-05	400	1.00E-06	1.14E-01	2.19E-03
24	0.38	1.00E-05	400	1.00E-06	1.10E-01	2.28E-03
25	0.38	1.00E-05	400	1.00E-06	1.05E-01	2.38E-03
26	0.38	1.00E-05	400	1.00E-06	1.01E-01	2.47E-03
27	0.38	1.00E-05	400	1.00E-06	9.75E-02	2.57E-03
28	0.38	1.00E-05	400	1.00E-06	9.40E-02	2.66E-03
29	0.38	1.00E-05	400	1.00E-06	9.07E-02	2.76E-03
30	0.38	1.00E-05	400	1.00E-06	8.77E-02	2.85E-03

Exhibit 2. Results Obtained By Changing The Value k.

t	k	SF	CDI	TR	$(1-e^{(-kt)})/(kt)$	PRG
yr	yr-1	risk/pCi	cm^2	risk	unitless	pCi/cm^2
30	0.000001	1.00E-05	400	1.00E-06	1.00E+00	2.50E-04
30	0.033331	1.00E-05	400	1.00E-06	6.32E-01	3.95E-04
30	0.066661	1.00E-05	400	1.00E-06	4.32E-01	5.78E-04
30	0.099991	1.00E-05	400	1.00E-06	3.17E-01	7.89E-04
30	0.133321	1.00E-05	400	1.00E-06	2.45E-01	1.02E-03
30	0.166651	1.00E-05	400	1.00E-06	1.99E-01	1.26E-03
30	0.199981	1.00E-05	400	1.00E-06	1.66E-01	1.50E-03
30	0.233311	1.00E-05	400	1.00E-06	1.43E-01	1.75E-03
30	0.266641	1.00E-05	400	1.00E-06	1.25E-01	2.00E-03
30	0.299971	1.00E-05	400	1.00E-06	1.11E-01	2.25E-03
30	0.333301	1.00E-05	400	1.00E-06	1.00E-01	2.50E-03
30	0.366631	1.00E-05	400	1.00E-06	9.09E-02	2.75E-03
30	0.399961	1.00E-05	400	1.00E-06	8.33E-02	3.00E-03
30	0.433291	1.00E-05	400	1.00E-06	7.69E-02	3.25E-03
30	0.466621	1.00E-05	400	1.00E-06	7.14E-02	3.50E-03
30	0.499951	1.00E-05	400	1.00E-06	6.67E-02	3.75E-03
30	0.533281	1.00E-05	400	1.00E-06	6.25E-02	4.00E-03
30	0.566611	1.00E-05	400	1.00E-06	5.88E-02	4.25E-03

30	0.599941	1.00E-05	400	1.00E-06	5.56E-02	4.50E-03
30	0.633271	1.00E-05	400	1.00E-06	5.26E-02	4.75E-03
30	0.666601	1.00E-05	400	1.00E-06	5.00E-02	5.00E-03
30	0.699931	1.00E-05	400	1.00E-06	4.76E-02	5.25E-03
30	0.733261	1.00E-05	400	1.00E-06	4.55E-02	5.50E-03
30	0.766591	1.00E-05	400	1.00E-06	4.35E-02	5.75E-03
30	0.799921	1.00E-05	400	1.00E-06	4.17E-02	6.00E-03
30	0.833251	1.00E-05	400	1.00E-06	4.00E-02	6.25E-03
30	0.866581	1.00E-05	400	1.00E-06	3.85E-02	6.50E-03
30	0.899911	1.00E-05	400	1.00E-06	3.70E-02	6.75E-03
30	0.933241	1.00E-05	400	1.00E-06	3.57E-02	7.00E-03
30	0.966571	1.00E-05	400	1.00E-06	3.45E-02	7.25E-03
30	1	1.00E-05	400	1.00E-06	3.33E-02	7.50E-03

4.3.9 Dermal Exposure

Other possible exposure pathways that may be considered in a radiological analysis of a contaminated building would include internal contamination due to puncture wounds and dermal absorption of radionuclides deposited on the skin. The radiation doses caused by these two pathways, however, are likely to be *de minimis* and much smaller than the doses caused by the other potential pathways already considered for most radionuclides (Kennedy and Strenge 1992 in Section 3.1.2). Therefore, dermal pathways are not included in the current version of this BPRG calculator. If one desires to calculate dermal risk, one method would be to calculate the dose based on adherence of dust/soil to dry or wet skin. The mobility of the radionuclide, the range of the emitted beta particles, and the assumed exposure parameters may be used to determine the percentage contribution of each component to the total calculated risk. The partitioning coefficient (Kd) of the beta-emitting radionuclide of concern would be used to determine the significance of the sweat layer. If this value approaches zero, then contaminated soil particulates may dissolve, and diluted concentrations should be estimated from the original soil concentrations. If Kd is greater than zero, then the range of the emitted beta particles is expected to become the most important factor in determining if the radionuclide yields an unacceptable dose. If the range exceeds the average distribution of the sweat layer, then risk calculations are likely warranted. The dry deposition scenario dominates the whole exposure interval. Otherwise, the radionuclide is shielded by the sweat layer, and the corresponding indirect deposition contributions to the total risk are negligible.

4.3.10 Room Surfaces Factor ($F_{r\text{-}surf}$)

The 3-D direct external exposure equations (building materials and dust) without $F_{r\text{-}surf}$ are single surface equations. The surfaces factor, in the recommended default and site-specific equations, is based on exposure to 4 walls, the floor, and the ceiling in a room. This calculator uses the relationship between the dose rate coefficients for exposures in a contaminated room and dose rate coefficients for an infinite source to calculate a surfaces factor ($F_{r\text{-}surf}$). The dose quantity evaluated is the air kerma rate one meter above the floor. The floor, walls, and ceiling of the rooms are assumed to be contaminated to the same level. In Finklea 2015, 5 room sizes, ranging from 10 by 10 by 10 to 400 by 400 by 40 feet, were modeled to account for the dose contribution from multiple surfaces. Several individual materials, including wood, glass, concrete, drywall and adobe mud brick, were analyzed as well as 2 composite scenarios where multiple building materials are present in different ratios. Composite 1 is a drywall room with a glass window, wooden doors, and drywall walls. The floors for composite 1 are concrete and the ceiling is drywall. Composite 2 is a concrete room with wooden doors, a drywall ceiling, and a concrete floor. Both composite cases used a homogeneous mix of material for the walls to represent the window and door mixed in with the wall. Four receptor positions were included for each material: average, center of room, corner of room, and along the center of a wall. Contamination depths were considered to be surface, 1cm, 5cm, 15cm, and 100cm (infinite). The $F_{r\text{-}surf}$ for the default option is set to the most protective value across the 5 room sizes and 4 receptor positions. In the site-specific option, the user can select from the 5 room sizes, 4 receptor positions, and the building material. Finklea 2015 presents the air kerma values; additional appendices were developed for this BDCC Calculator to give the ratios compared to infinite dose coefficients. The $F_{r\text{-}surf}$ values for parent nuclides for adobe and concrete are given in Appendix A and B. The $F_{r\text{-}surf}$ values for parent nuclides for drywall, glass, and wood are given in Appendices C, D, and E. The $F_{r\text{-}surf}$ values for parent nuclides for room composite 1 are given in Appendix F. The $F_{r\text{-}surf}$ values for parent nuclides for room composite 2 are given in Appendix G. The $F_{r\text{-}surf}$ values for the "+D" nuclides are given in Appendix H. The $F_{r\text{-}surf}$ values for the "+E" nuclides are given in Appendix I.

4.3.11 Radionuclide Decay Constant (λ)

The decay constant term (λ), which is based on the half-life of the isotope, is used for some media in nearly all land uses. $\lambda = 0.693/\text{half-life}$ in years (where $0.693=\ln(2)$). The term $(1 - e^{-\lambda t})$ takes into account the number of half-lives that will occur within the exposure duration to calculate an appropriate value. For the secular equilibrium BPRG output option, decay is not used. In most cases, site-specific analytical data should be used to establish the actual degree of equilibrium between each parent radionuclide and its decay products in each media sampled. However, in the absence of empirical data, the secular equilibrium BPRGs will provide a protective screening value. Definitions of the input variables are in Table 1.

4.3.12 Gamma Shielding Factors (GSF_a and GSF_b)

A shielding factor, GSF_a, was added to the air submersion equations with a default of 1 (no shielding). If the user has a site-specific shielding factor, it can be applied in the calculator.

A shielding factor, GSF_b, was added to the 3-D building equations with a default of 1 (no shielding). If the user has a site-specific shielding factor, it can be applied in the calculator.

4.4 Equation Sources and Parameters

This section presents details on some of the equation sources and parameters.

4.4.1 Exposure to Settled Dust on Surfaces Equations

Inadvertent ingestion from materials deposited on surfaces equation was modeled after the equation found in ANL 2001 (Fig 8.3). The ingestion rate term in this equation was modeled after EPA 2003 (pg. D-4).

External exposure from deposited materials equation was modeled after the equation found in ANL 2001 (Fig 8.7).

4.4.2 Ambient Air Exposure

The inhalation equation was modeled after the equation found in EPA 2003 (pg. D-1).

The submersion equation was modeled after the equation found in ANL 2001 (Fig 8.1)

4.4.2.1 Submersion Pathway Equation Derivation

The air submersion external dose from exposure to indoor contaminated air was calculated by using the following equation:

$$D^n_{i,sub}(t) = F_{in} \times F_i \times C^n_i(t) \times DCF^n_{sub},$$

where:

F_{in} = fraction of time spent indoors;

F_i = fraction of time spent in compartment *i*;

$D^n_{i,sub}(t)$ = total annual air submersion effective dose equivalent from radionuclide *n* at time t in compartment *i* (mrem/yr);

$C^n_i(t)$ = average concentration of radionuclide *n* at time *t* in the indoor air of compartment *i* (pCi/m^3); and

$DCF^n_{sub}(t)$ = air submersion DCF for radionuclide *n* (mrem/yr per pCi/m^3).

4.4.3 External Exposure

The direct external exposure from the volume and surface of a large area equation was modeled after ANL 2001 (Fig 8.6). External exposure from deposited materials equation was modeled after the equation found in ANL 2001 (Fig 8.7).

4.4.3.1 External Exposure Equation Derivation

The external exposure pathway dose from exposure to an area or a volume source containing radionuclide *n* in compartment *i*,

D^n_{ir} , is expressed as:

$$D^n_{ir} = F_{in} \times F_i \times C^n_i \times DCF^n_r \times F^n_G,$$

where:

F_{in} = fraction of time spent indoors;

F_i = fraction of time spent in compartment *i*;

C_n =average concentration of radionuclide n

DCF_n = FGR-12 dose conversion factor for infinite volume source; and

F_G^n = geometrical factor for finite area, source thickness, shielding, source material, and position of receptor relative to the source for radionuclide *n*.

The geometrical factor is the ratio of the effective dose equivalent for the actual source to the effective dose equivalent for the standard source. The standard source is a contaminated soil of infinite depth and lateral extent with no cover. The geometrical factor is expressed as the product of the depth-and-cover factor, F_{CD}, an area and material factor, F_{AM}, and the off-set factor, $F_{OFF\text{-}SET}$.

So,
F_G^n = effective dose from actual source/effective dose from standard source.

Then,
$F_G^n = F_{CD} \times F_{AM} \times F_{OFF\text{-}SET}$

4.4.3.1.1 Depth-And-Cover Factor (F_{CD})

Note: The F_{CD} would traditionally be included in this type of analysis; however, it is not included in the equations for this calculator. This calculator includes depth-specific dose conversion factors for surface (ground plane) and uniformly distributed volume sources at four specific thicknesses (1 cm, 5 cm, 15 cm, and effectively infinite). Inclusion of these dose conversion factors eliminates the need for the F_{CD}.

Dose conversion factors in FGR-12 (Eckerman and Ryman 1993) are given for surface and uniformly distributed volume sources at four specific thicknesses (1 cm, 5 cm, 15 cm, and effectively infinite) with a soil density of 1.6 g/cm^3. FGR-12 assumes that sources are infinite in lateral extent. In actual situations, sources can have any depth, shape, cover, and size. A depth and-cover factor function, F_{CD}, was developed with regression analysis to express the attenuation for radionuclides. Three independent radionuclide-specific parameters were determined by using the effective dose equivalent values of FGR-12 at different depths. Kamboj et al. (1998) describes how the depth-and-cover function was derived using the effective dose equivalent values of FGR-12 at different depths. A depth-and-cover factor function was derived from the depth factor function by considering both dose contribution and attenuation from different depths.

$$\frac{D(T_c = t_c, T_s = t_s)}{D(T_c = 0, T_s = \infty)} = Ae^{-K_A\rho_c t_c}(1 - e^{-K_A\rho_s t_s}) + Be^{-K_B\rho_c t_c}(1 - e^{-K_B\rho_s t_s}),$$

where:

A, B = fit parameters (dimensionless);

K_A, K_B = fit parameters (cm^2/g);

t_c = shielding thickness (cm) (the sum of all shielding thicknesses between the source and the receptor), the shielding is placed immediately adjacent to the source;

ρ_c= shielding density (g/cm^3)(the thickness-averaged density between the source and receptor);

t_s = source thickness (cm);

ρ_s = source density (g/cm^3);

T_c = shielding parameter (m); and

T_s = source depth parameter (m).

The following constraints were put on the four fitting parameters:

1. All the parameters were forced to be positive;

2. A + B = 1; and

3. In the limit source depth, $t_s \rightarrow$ zero, the DCF should match the contaminated surface DCF.

All the four unknown parameters (A, B, K_A, and K_B) were found for 67 radionuclides available in the RESRAD-BUILD computer code. The fitted values of A, B, K_A, and K_B for radionuclides were used in the dose calculations.

4.4.3.1.2 Area-And-Material Factor (F_{AM})

For actual geometries (finite area and different materials), the area and material factor, F_{AM}, was derived by using the point-kernel method. This factor depends not only on the lateral extent of the contamination but also on source thickness, shielding thickness, gamma energies, and source material through its attenuation and buildup factors. All energies from radionuclide decay were considered separately and weighted by its yield, y, energy, E, and an energy dependent coefficient, K, to convert from air-absorbed dose to effective dose equivalent.

$$F_{AM} = \frac{\sum_{Energies j} y_j E_j K_j \int_{V'} \frac{B(\chi)e^{-\mu x'}}{(x')^2} dV'}{\sum_{Energies j} y_j E_j K_j \int_{V} \frac{B(\chi)e^{-\mu x}}{(x)^2} dV},$$

where:

$(x')^2 = r^2 + (t_a + t_c + t)^2$;

$(x)^2 = r^2 + (1m + t)^2$;

$$\mu = \frac{(t_a\mu_a + t_c\mu_c + t\mu_s)}{(t_a + t_c + t)}, \quad \text{and}$$

$$B(\chi) = B_a\left(\frac{t_a}{t_a + t_c + t_s}\chi\right) B_c\left(\frac{t_c}{t_a + t_c + t_s}\chi\right) B_s\left(\frac{t_s}{t_a + t_c + t_s}\chi\right)$$

B and μ are the buildup factor and the attenuation factor, respectively, for the appropriate material (*a* for air, *c* for shield material, and *s* for source material or soil reference). The integration volume V' is the desired geometry of specified material with radius R, shielding thickness t_c, and air thickness t_a; whereas V is the reference geometry of soil extending infinitely laterally with no shield and the receptor midpoint located 1 m from the surface.

4.4.3.1.3 Off-set Factor ($F_{OFF-SET}$)

The off-set factor, $F_{OFF-SET}$, is the ratio of the dose estimates from a noncircular shaped contaminated material to a reference shape. The concept of the shape factor is used to calculate the off-set factor. The reference shape is a fully contaminated circular area encompassing the given shape, centered about the receptor. This factor is derived by considering the area, material factors of a series of concentric circles, and the corresponding contamination fraction of the annular regions. The off-set factor is obtained by enclosing the irregularly shaped contaminated area in a circle; multiplying the area factor of each annulus by the fraction of the contaminated annulus area, f_i; summing the products; and dividing by the area factor of a circular contaminated material that is equivalent in area.

$$F_{OFF-SET} = \frac{\sum_{i=0}^{n} f_i\left[F_{AM}(A_i) - F_A(A_{i-1})\right]}{F_{AM}\left[\sum_{i=0}^{n} f_i(A_i - A_{i-1})\right]}$$

5. Recommended Default Exposure Parameters

Table 1 presents the definitions of the variables and their default values. The BPRG default values and exposure models are consistent with the Dose Compliance Concentrations for Radionuclides in Buildings (BDCC) calculator. Both the BPRG and BDCC default values are consistent with the World Trade Center Assessment (EPA 2003), where the same pathways are addressed (e.g., ingestion and inhalation) and are analogous where pathways are similar (e.g., dermal and external exposure), except where the BDCC and BPRG have been updated to both follow the recommendations in the OSWER Directive concerning use of exposure parameters from the 2011 Exposure Factors Handbook. Any alternative values or assumptions used in remedy evaluation or selection on a CERCLA site should be presented with supporting rationale in Administrative Records.

Table 1. Recommended Default Exposure Parameters

BPRG Equations

Symbol ▾	Definition (units)	Default	Reference
			Exposure to 15cm of contaminated dust on

$BPRG_{iw\text{-}3D\text{-}ext\text{-}15cm}$	Indoor Worker 3-D Direct External Exposure (pCi/g)	Isotope-specific	surfaces of building material. Developed for BPRG calculator.
$BPRG_{iw\text{-}3D\text{-}ext\text{-}1cm}$	Indoor Worker 3-D Direct External Exposure (pCi/g)	Isotope-specific	Exposure to 1cm of contaminated dust on surfaces of building material. Developed for BPRG calculator.
$BPRG_{iw\text{-}3D\text{-}ext\text{-}5cm}$	Indoor Worker 3-D Direct External Exposure (pCi/g)	Isotope-specific	Exposure to 5cm of contaminated dust on surfaces of building material. Developed for BPRG calculator.
$BPRG_{iw\text{-}3D\text{-}ext\text{-}gp}$	Indoor Worker 3-D Direct External Exposure (pCi/cm^2)	Isotope-specific	Exposure to ground plane contaminated dust on surfaces of building material. Developed for BPRG calculator.
$BPRG_{iw\text{-}3D\text{-}ext\text{-}sv}$	Indoor Worker 3-D Direct External Exposure (pCi/g)	Isotope-specific	Exposure to infinite depth soil volume on building material. Developed for BPRG calculator.
$BPRG_{iw\text{-}air\text{-}decay\text{-}inh}$	Indoor Worker Inhalation of Ambient Air (with half-life decay) (pCi/m^3)	Isotope-specific	Developed for BPRG calculator.
$BPRG_{iw\text{-}air\text{-}decay\text{-}sub}$	Indoor Worker Submersion in Ambient Air (with half-life decay) (pCi/m^3)	Isotope-specific	Developed for BPRG calculator.
$BPRG_{iw\text{-}air\text{-}decay\text{-}tot}$	Indoor Worker Total Exposure to Ambient Air (with half-life decay) (pCi/m^3)	Isotope-specific	Developed for BPRG calculator.
$BPRG_{iw\text{-}air\text{-}nodecay\text{-}inh}$	Indoor Worker Inhalation of Ambient Air (with no half-life decay) (pCi/m^3)	Isotope-specific	Developed for BPRG calculator. Exposure to ambient air.
$BPRG_{iw\text{-}air\text{-}nodecay\text{-}sub}$	Indoor Worker Submersion in Ambient Air (with no half-life decay) (pCi/m^3)	Isotope-specific	Developed for BPRG calculator. Exposure to ambient air.
$BPRG_{iw\text{-}air\text{-}nodecay\text{-}tot}$	Indoor Worker Total Exposure to Ambient Air (with no half-life decay) (pCi/m^3)	Isotope-specific	Developed for BPRG calculator. Exposure to ambient air.
$BPRG_{iw\text{-}dust\text{-}ext}$	Indoor Worker External Exposure to Settled Dust on Room Surfaces (pCi/cm^2)	Isotope-specific	Developed for BPRG calculator.
$BPRG_{iw\text{-}dust\text{-}ing}$	Indoor Worker Ingestion of Settled Dust on Room Surfaces (pCi/cm^2)	Isotope-specific	Developed for BPRG calculator.
$BPRG_{iw\text{-}dust\text{-}tot}$	Indoor Worker Total Exposure to Settled Dust on Room Surfaces (pCi/cm^2)	Isotope-specific	Developed for BPRG calculator.
$BPRG_{res\text{-}3D\text{-}ext\text{-}15cm}$	Resident 3-D Direct External Exposure (pCi/g)	Isotope-specific	Exposure to 15cm of contaminated dust on surfaces of building material. Developed for BPRG calculator.
$BPRG_{res\text{-}3D\text{-}ext\text{-}1cm}$	Resident 3-D Direct External Exposure (pCi/g)	Isotope-specific	Exposure to 1cm of contaminated dust on surfaces of building material. Developed for BPRG calculator.
$BPRG_{res\text{-}3D\text{-}ext\text{-}5cm}$	Resident 3-D Direct External Exposure (pCi/g)	Isotope-specific	Exposure to 5cm of contaminated dust on surfaces of building material. Developed for BPRG calculator.
$BPRG_{res\text{-}3D\text{-}ext\text{-}gp}$	Resident 3-D Direct External Exposure (pCi/cm^2)	Isotope-specific	Exposure to ground plane contaminated dust on surfaces of building material. Developed for BPRG calculator.
$BPRG_{res\text{-}3D\text{-}ext\text{-}sv}$	Resident 3-D Direct External Exposure (pCi/g)	Isotope-specific	Exposure to infinite depth soil volume on building material. Developed for BPRG calculator.

$BPRG_{res\text{-}air\text{-}decay\text{-}inh}$	Resident Inhalation of Ambient Air (with half-life decay) (pCi/m^3)	Isotope-specific	Developed for BPRG calculator.
$BPRG_{res\text{-}air\text{-}decay\text{-}sub}$	Resident Submersion in Ambient Air (with half-life decay) (pCi/m^3)	Isotope-specific	Developed for BPRG calculator.
$BPRG_{res\text{-}air\text{-}decay\text{-}tot}$	Resident Total Exposure to Ambient Air (with half-life decay) (pCi/m^3)	Isotope-specific	Developed for BPRG calculator.
$BPRG_{res\text{-}air\text{-}nodecay\text{-}inh}$	Resident Inhalation of Ambient Air (with no half-life decay) (pCi/m^3)	Isotope-specific	Developed for BPRG calculator. Exposure to ambient air.
$BPRG_{res\text{-}air\text{-}nodecay\text{-}sub}$	Resident Submersion in Ambient Air (with no half-life decay) (pCi/m^3)	Isotope-specific	Developed for BPRG calculator. Exposure to ambient air.
$BPRG_{res\text{-}air\text{-}nodecay\text{-}tot}$	Resident Total Exposure to Ambient Air (with no half-life decay) (pCi/m^3)	Isotope-specific	Developed for BPRG calculator. Exposure to ambient air.
$BPRG_{res\text{-}dust\text{-}ext}$	Resident External Exposure to Settled Dust on Room Surfaces (pCi/cm^2)	Isotope-specific	Developed for BPRG calculator.
$BPRG_{res\text{-}dust\text{-}ing}$	Resident Ingestion of Settled Dust on Room Surfaces (pCi/cm^2)	Isotope-specific	Developed for BPRG calculator.
$BPRG_{res\text{-}dust\text{-}tot}$	Resident Total Exposure to Settled Dust on Room Surfaces (pCi/cm^2)	Isotope-specific	Developed for BPRG calculator.

Slope Factors

Symbol	Definition (units)	Default	Reference
$SF_{ext\text{-}15cm}$	External Exposure Slope Factor - direct (risk/yr per pCi/g)	Isotope-specific	ORNL 2014c
$SF_{ext\text{-}1cm}$	External Exposure Slope Factor - direct (risk/yr per pCi/g)	Isotope-specific	ORNL 2014c
$SF_{ext\text{-}5cm}$	External Exposure Slope Factor - direct (risk/yr per pCi/g)	Isotope-specific	ORNL 2014c
$SF_{ext\text{-}gp}$	External Exposure Slope Factor - dust (risk/yr per pCi/cm^2)	Isotope-specific	ORNL 2014c
$SF_{ext\text{-}sv}$	External Exposure Slope Factor - direct (risk/yr per pCi/g)	Isotope-specific	ORNL 2014c
SF_i	Inhalation Slope Factor - air (risk/pCi)	Isotope-specific	ORNL 2014c
SF_o	Dust Ingestion Slope Factor - population (risk/pCi)	Isotope-specific	ORNL 2014c
SF_{oa}	Dust Ingestion Slope Factor - adult only (risk/pCi)	Isotope-specific	ORNL 2014c
SF_{sub}	External Exposure Slope Factor - submersion (risk/yr per pCi/m^3)	Isotope-specific	ORNL 2014c

Dose and Decay Constant Variables

Symbol	Definition (units)	Default	Reference
k	Dissipation Rate Constant - (yr^{-1})	0.0	EPA 2003 (pg. D-8)
t_{iw}	Time - indoor worker (yr)	25	U.S. EPA 2014 (Attachment 1)

TR	Target Risk	1E-06	EPA 1990 (pg. 8718-8719)
t_{res}	Time - resident (yr)	26	U.S. EPA 2014 (Attachment 1)
λ	decay constant = 0.693/half-life (year^{-1}) where 0.693 = ln(2)	Isotope-specific	Developed for Radionuclide Soil Screening Calculator (EPA 2000c)

Miscellaneous Variables

Symbol	Definition (units)	Default	Reference
F_{AM}	Area and Material Factor (unitless)	1.0	ANL 2001 (Fig 8.6)
F_i	Fraction of time spent in compartment (unitless)	1.0	ANL 2001 (Fig 8.1)
F_{in}	Fraction time spent indoors (unitless)	1.0	ANL 2001 (Fig 8.1)
$F_{OFF\text{-}SET}$	Off-set Factor (unitless)	1.0	ANL 2001 (Fig 8.6)
FQ_{iw}	Frequency of Hand to Mouth - indoor worker (event/hr)	3	EPA 2011 Table 4.1 and EPA 2003. Time weighted average of all age groups from 6 to 26 years.
$FQ_{res\text{-}a}$	Frequency of Hand to Mouth - adult (event/hr)	3	EPA 2011 Table 4.1 and EPA 2003. Time weighted average of all age groups from 6 to 26 years.
$FQ_{res\text{-}c}$	Frequency of Hand to Mouth - child (event/hr)	17	EPA 2011 Table 4.1 and EPA 2003. Time weighted average of all age groups from birth to 6 years.
$F_{r\text{-}surf^{15cm}}$	Room Surfaces Factor for 15 cm Soil Volume (unitless)	Isotope-specific	Finklea 2015
$F_{r\text{-}surf^{1cm}}$	Room Surfaces Factor for 1 cm Soil Volume (unitless)	Isotope-specific	Finklea 2015
$F_{r\text{-}surf^{5cm}}$	Room Surfaces Factor for 5 cm Soil Volume (unitless)	Isotope-specific	Finklea 2015
$F_{r\text{-}surf^{gp}}$	Room Surfaces Factor for Ground Plane (unitless)	Isotope-specific	Finklea 2015
$F_{r\text{-}surf^{sv}}$	Room Surfaces Factor for Infinite Soil Volume (unitless)	Isotope-specific	Finklea 2015
$FTSS_h$	Fraction Transferred Surface to Skin - hard surface (unitless)	0.5	EPA 2003 (pg. D-3)
$FTSS_s$	Fraction Transferred Surface to Skin - soft surface (unitless)	0.1	EPA 2003 (pg. D-3)
GSF_a	Gamma Shielding Factor for air (unitless)	1 (assumes no shielding)	Other GSFs are presented in these reports. U.S. EPA 2000a. (pg. 2-22). U.S. EPA 2000b. (pg. 2-18)
GSF_b	Gamma Shielding Factor for building surfaces (unitless)	1 (assumes no shielding)	Other GSFs are presented in these reports. U.S. EPA 2000a. (pg. 2-22). U.S. EPA 2000b. (pg. 2-18)
SA_{iw}	Surface Area of Fingers - indoor worker (cm^2)	49	EPA 2011 Table 7.2. 5% of the average of adult male and female.
$SA_{res\text{-}a}$	Surface Area of Fingers - adult (cm^2)	49	EPA 2011 Table 7.2. 5% of the average of adult male and female.

SA_{res-c}	Surface Area of Fingers - child (cm^2)	16	EPA 2011 Table 7.2. 5% of the average of chld male and female.
SE	Saliva Extraction Factor (unitless)	0.5	EPA 2003 (pg. D-5)

Inhalation and Ingestion Rates

Symbol	Definition (units)	Default	Reference
$IFA_{res-adj}$	Age-Adjusted Inhalation Fraction - resident (m^3; based on IRIS default)	161,000	U.S. EPA 1991 (pg. 15)
IFD_{iw}	Dust Ingestion Factor - indoor worker (cm^2/day)	176.4	Calculated Value based on EPA 2003 (pg. D-4)
$IFD_{res-adj}$	Age-Adjusted Dust Ingestion Fraction - resident (cm^2)	3,200,400	Calculated Value based on EPA 2003 (pg. D-4)
IRA_{iw}	Inhalation Rate - indoor worker (m^3/day; based on a rate of 2.5m^3/hr for 24hr)	60	U.S. EPA 1991 (pg. 15)
IRA_{res-a}	Inhalation Rate - adult resident (m^3/day; based on IRIS default)	20	U.S. EPA 1991 (pg. 15)
IRA_{res-c}	Inhalation Rate - child resident (m^3/day; based on IRIS default)	10	U.S. EPA 1997 (pg. 5-11)

Exposure Frequency, Exposure Duration, and Exposure Time Variables

Symbol	Definition (units)	Default	Reference
ED_{iw}	Exposure Duration - indoor worker (yr)	25	U.S. EPA 2014 (Attachment 1)
ED_{res}	Exposure Duration - resident (yr)	26	U.S. EPA 2014 (Attachment 1)
ED_{res-a}	Exposure Duration - adult resident (yr)	20	U.S. EPA 2014 (Attachment 1)
ED_{res-c}	Exposure Duration - child resident (yr)	6	U.S. EPA 2014 (Attachment 1)
EF_{iw}	Exposure Frequency - indoor worker (days/yr)	250	U.S. EPA 2014 (Attachment 1)
EF_{res}	Exposure Frequency - resident (day/yr)	350	U.S. EPA 2014 (Attachment 1)
EF_{res-a}	Exposure Frequency - resident adult(day/yr)	350	U.S. EPA 2014 (Attachment 1)
EF_{res-c}	Exposure Frequency - resident child(day/yr)	350	U.S. EPA 2014 (Attachment 1)
ET_{iw}	Air Exposure Time - indoor worker (hr/day)	8	U.S. EPA 2014 (Attachment 1)
$ET_{iw,h}$	Exposure Time - indoor worker hard surface (hr/day)	4	EPA 2003 (pg. D-4)
$ET_{iw,s}$	Exposure Time - indoor worker soft surface (hr/day)	4	EPA 2003 (pg. D-4)
ET_{res}	Air Exposure Time - resident (hr/day)	24	U.S. EPA 2014 (Attachment 1)
ET_{res-a}	Air Exposure Time - resident adult(hr/day)	24	U.S. EPA 2014 (Attachment 1)

$ET_{res-a,h}$	Exposure Time - adult resident hard surface (hr/day)	6	EPA 2003 (pg. D-4)
$ET_{res-a,s}$	Exposure Time - adult resident soft surface (hr/day)	10	EPA 2003 (pg. D-4)
ET_{res-c}	Air Exposure Time - resident child(hr/day)	24	U.S. EPA 2014 (Attachment 1)
$ET_{res-c,h}$	Exposure Time - child hard surface (hr/day)	6	EPA 2003 (pg. D-4)
$ET_{res-c,s}$	Exposure Time - child soft surface (hr/day)	10	EPA 2003 (pg. D-4)

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